

# EIC Physics and ‘ePHENIX’

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Dec 11, 2015

Inaugural 'SPhenix/New RHIC Detector' Collaboration meeting  
Rutgers University

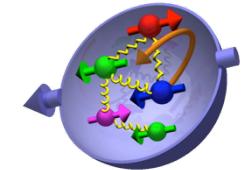
# Outline

- EIC Physics Highlights
- Detector Concept
- Detector Performance
- From 10 GeV to 20 GeV electron beam

# EIC Physics

Well developed and summarized in:  
INT EIC report: [arXiv:1108.1713](https://arxiv.org/abs/1108.1713)  
EIC White Paper: [arXiv:1212.1701](https://arxiv.org/abs/1212.1701)  
eRHIC Design Study: [arXiv:1409.1633](https://arxiv.org/abs/1409.1633)

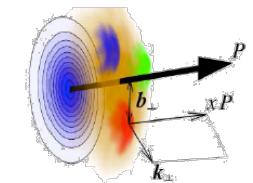
Distribution of quarks and gluons and their spins in space and momentum inside the nucleon



Nucleon helicity structure

Parton transverse motion in the nucleon

Spatial distribution of partons and parton orbital angular momentum

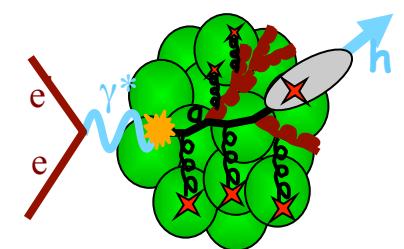


QCD in nuclei

Gluon saturation

Nuclear modification of parton distributions

Propagation/Hadronization in nuclear matter

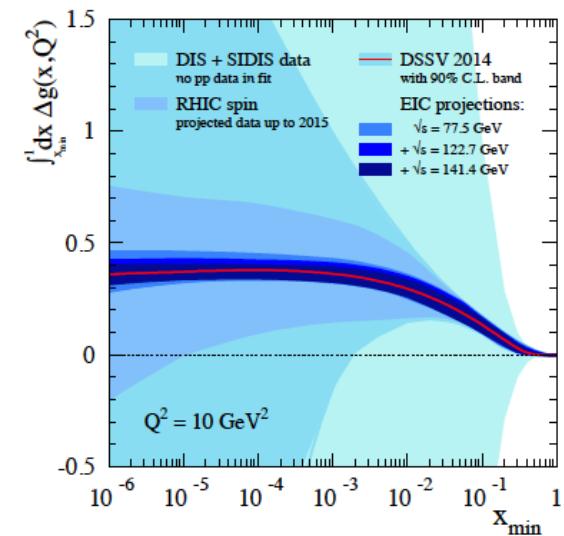


# Nucleon Helicity Structure

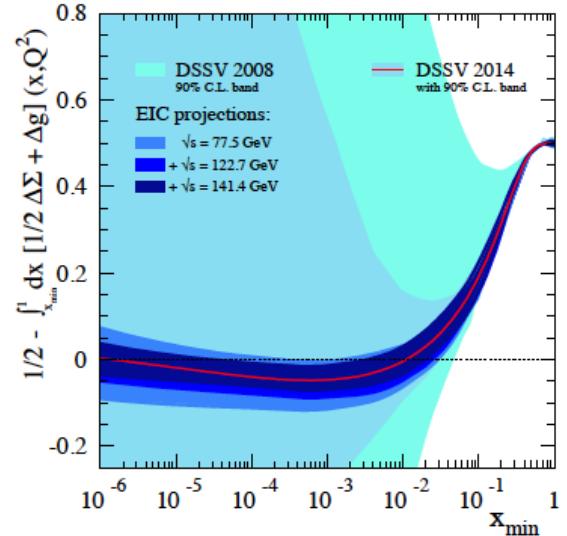
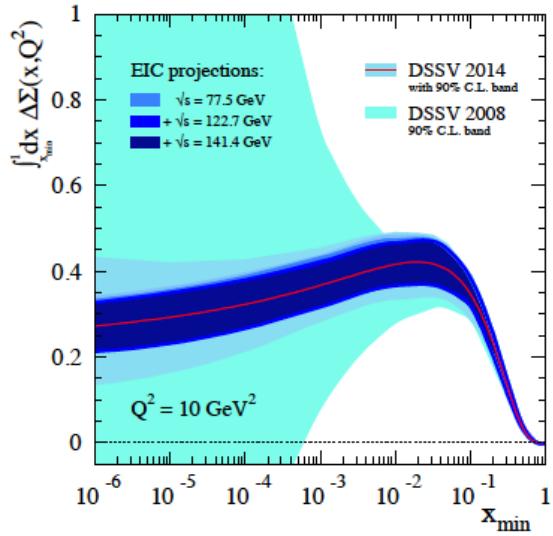
Inclusive DIS  
Semi-Inclusive DIS

$$\frac{1}{2} = \frac{1}{2} \sum_q [\Delta q + \Delta \bar{q}] + \Delta g + L$$

arXiv: 1509.06489



$1/2$  - Gluon - Quarks =

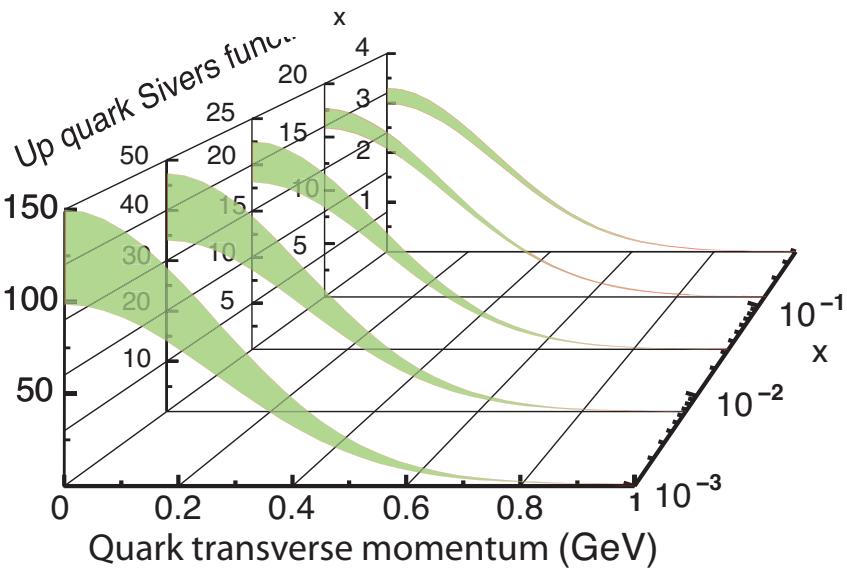
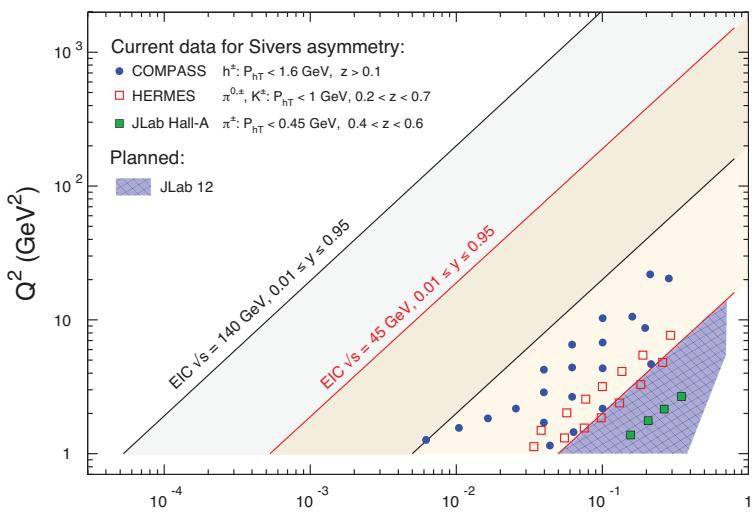


Orbital angular momentum

Spin puzzle will be solved

# Parton transverse motion in the nucleon

## Semi-Inclusive DIS

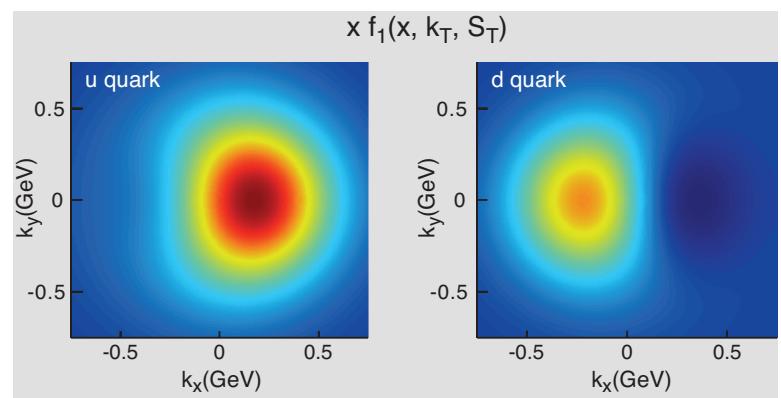


## Transverse Momentum Dependent PDF

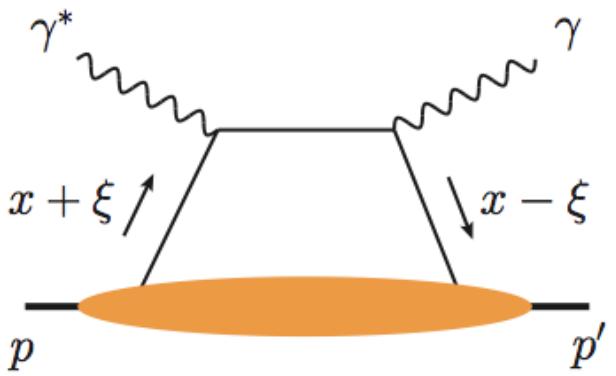
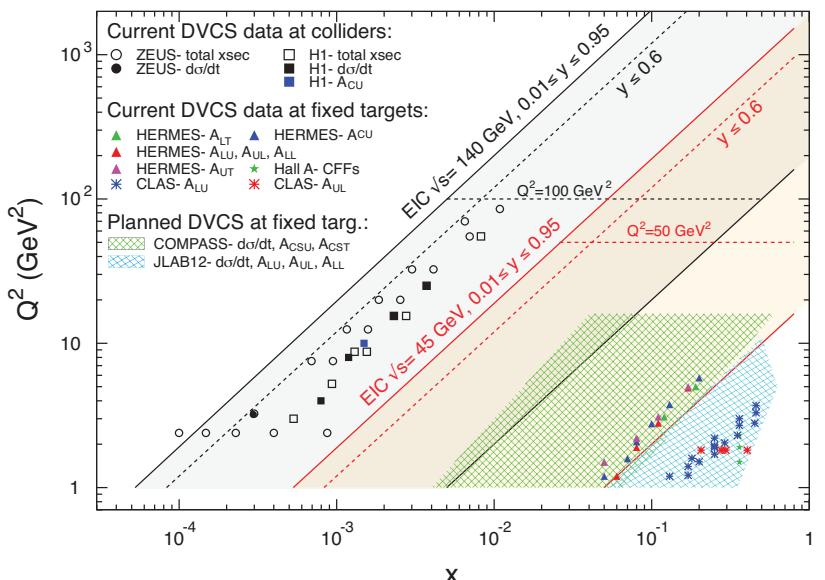
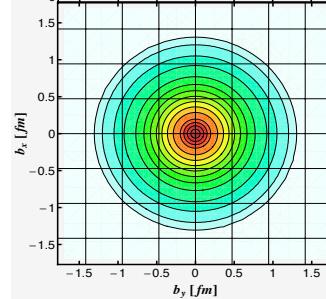
**Sivers:** links parton's intrinsic motion to the spin of the proton => **connection to the parton orbital motion**

Greatly expand  $x$ & $Q^2$  coverage

High luminosity => fully differential analysis over  $x$ ,  $Q^2$ ,  $z$  and  $P_{hT}$



# Parton spatial distribution: nucleon tomography



## Exclusive DIS

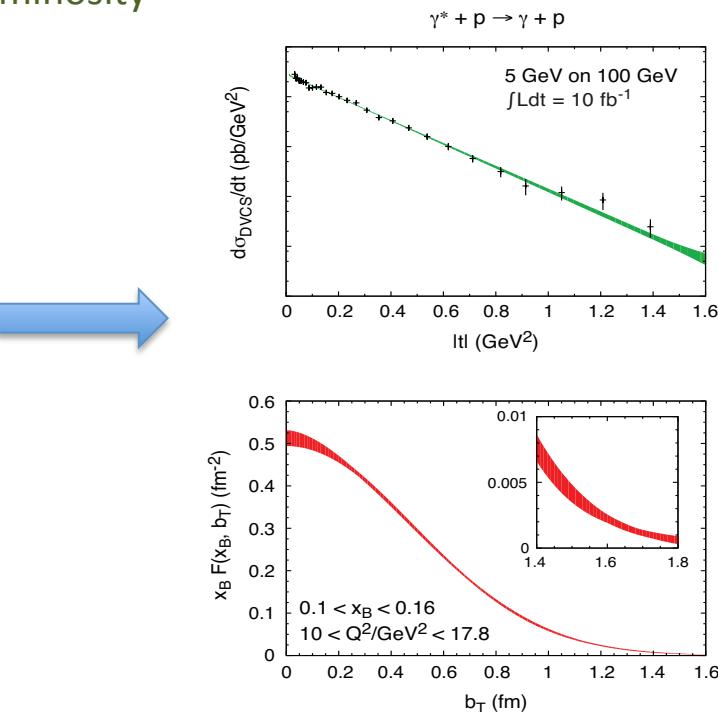
Generalized Parton Distributions (GPD)

Connected to parton orbital angular momentum

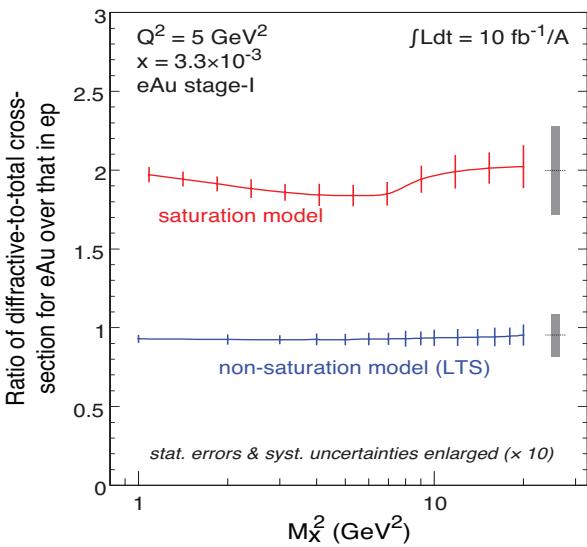
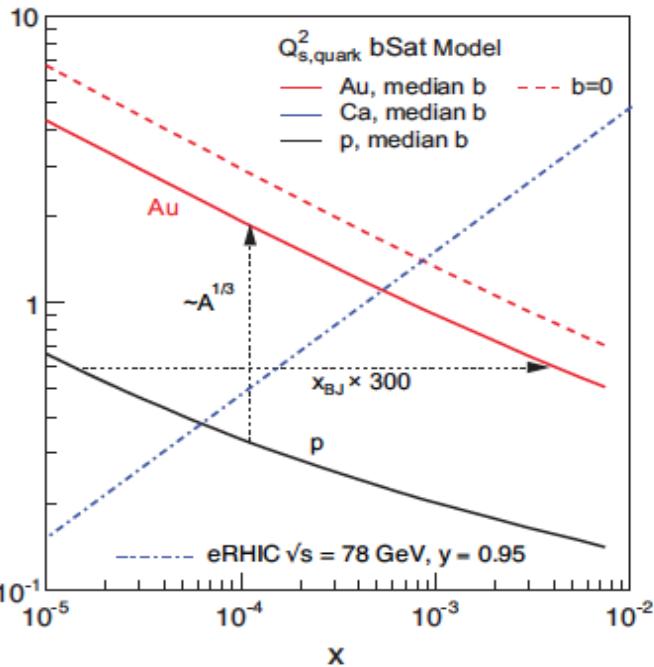
Existing data are either at low  $Q^2$  or have sizable stat. uncertainties

Provide data in wide  $x$ & $Q^2$

Precise imaging requires higher e-beam energy and luminosity



# Gluon Saturation



Color Glass Condensate (CGC)

High gluon density matter

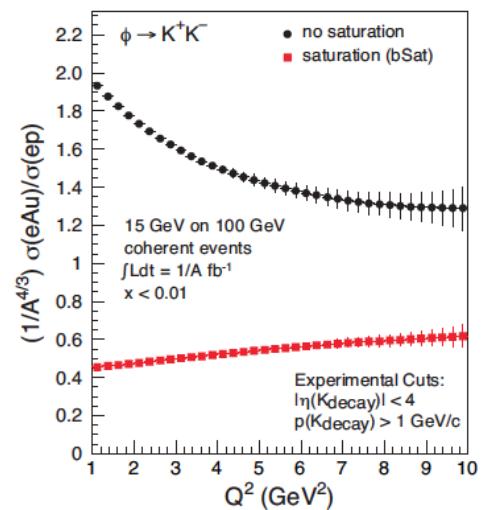
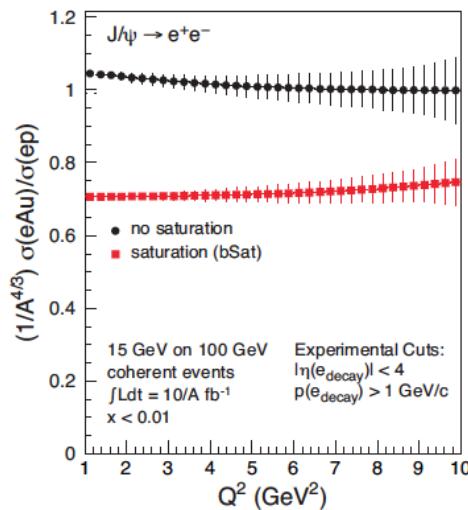
Direct consequence of gluon self-interaction in QCD

Saturation effects are greatly enhanced in eA collisions:

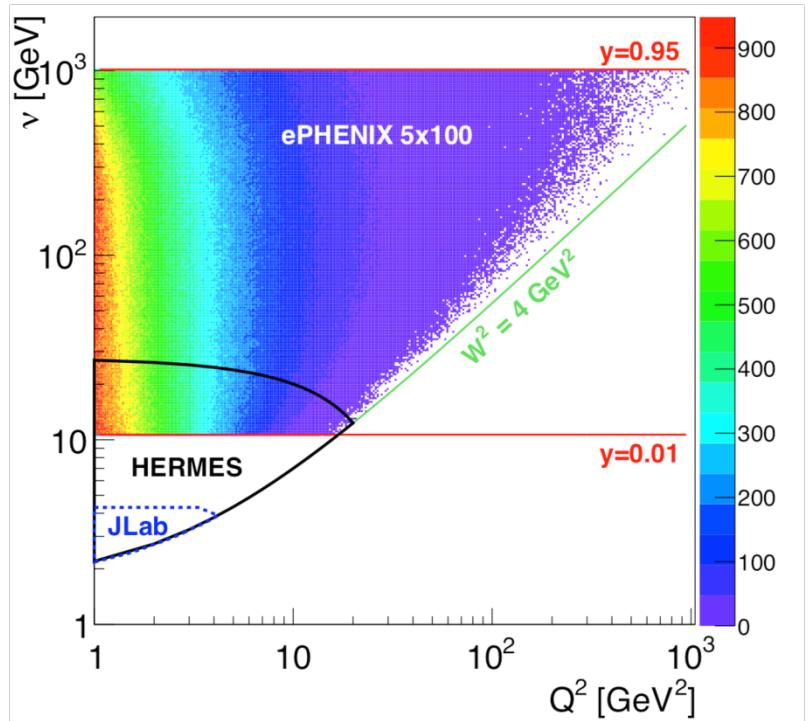
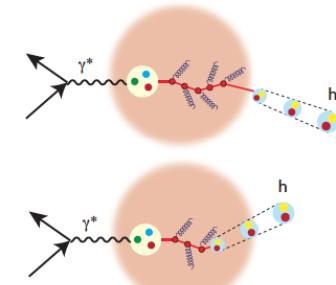
Collider energy  $\rightarrow$  low  $x$

Heavy Ions  $\rightarrow$  high  $A$

Diffractive:  $\sigma_{\text{diff}} \sim (xG)^2$



# Color Propagation and Hadronization



## Semi-inclusive eA

Probe color neutralization and hadronization

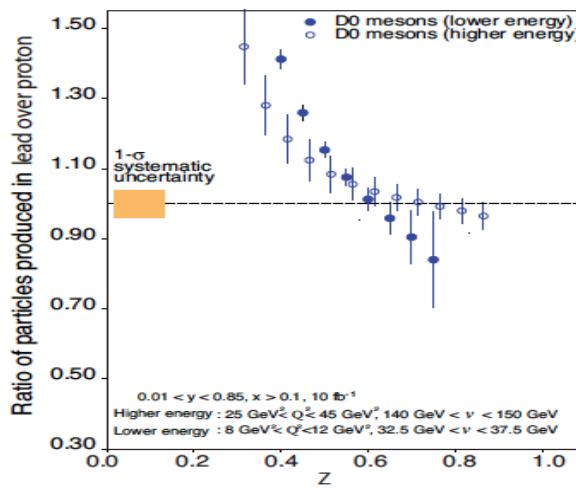
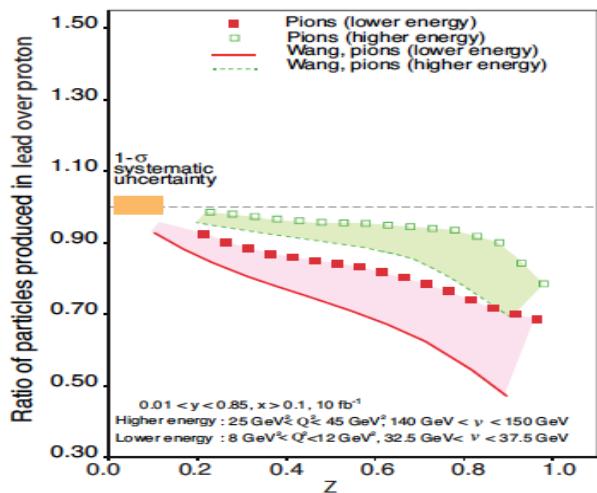
Different time&distance probed by varying nuclear size and parton energy

Previous experiments are limited by low  $\nu$ ,  $Q^2$   
eRHIC:

Much larger range of  $\nu$ ,  $Q^2$

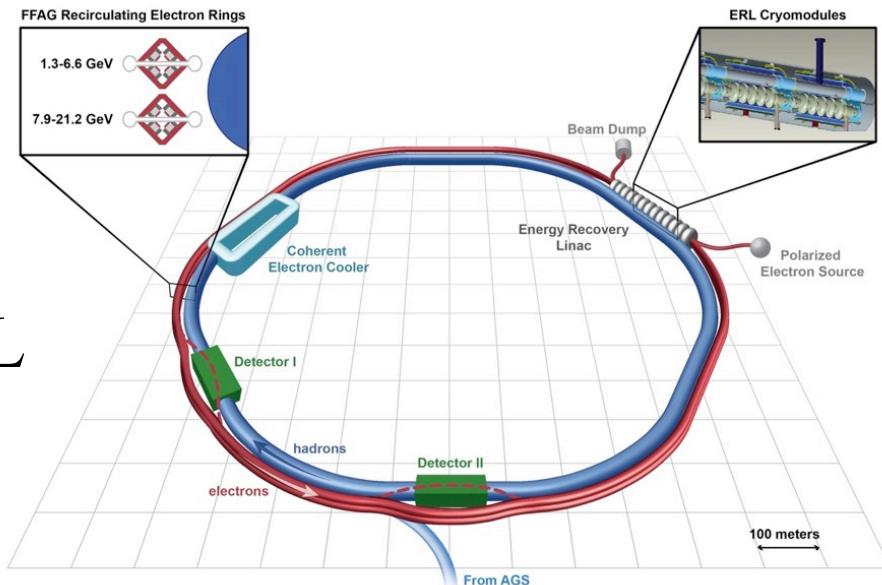
Wide range of nuclear size

Excellent ePHENIX hadron PID up to 60 GeV

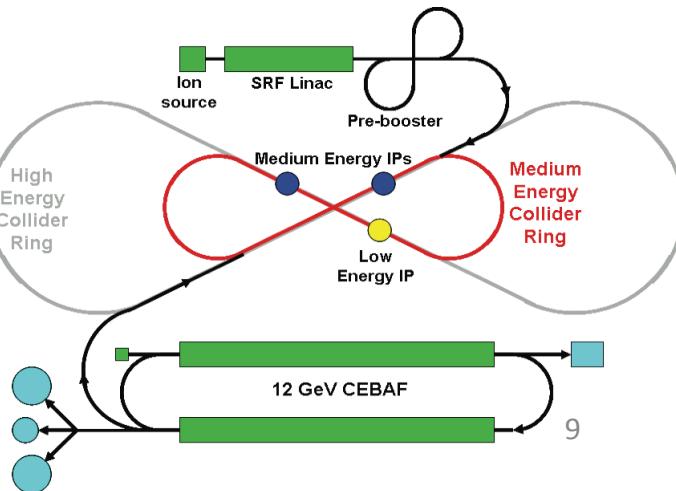


# EIC: ep/eA

BNL



JLab

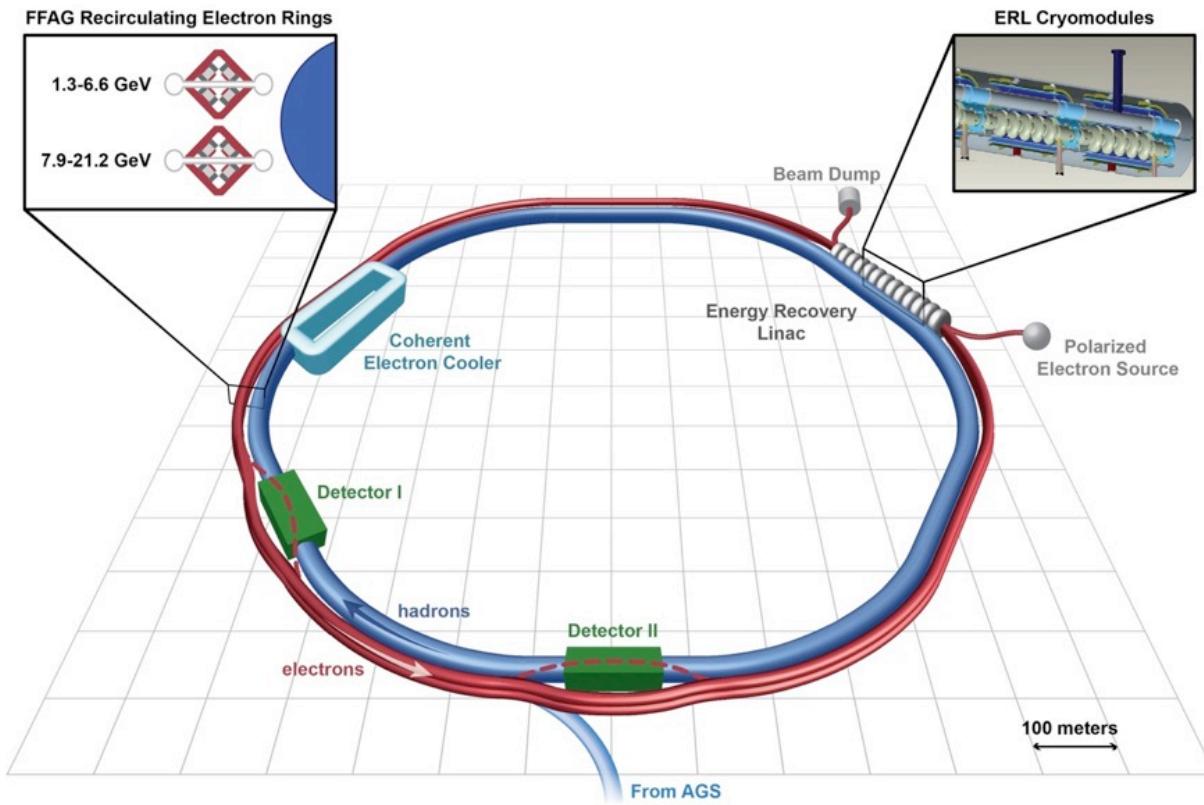


## 2015 Long Range Plan

We recommend a high-energy high-luminosity polarized **Electron Ion Collider** as the highest priority for new facility construction following the completion of FRIB.

# eRHIC

ep/eA



In current design:

Energy:

Electron: 6.6–21.2 GeV  
Proton: 25–250 GeV  
Ions: 10–100 GeV  
 $\sqrt{s}$ : up to 145 GeV

Polarization:

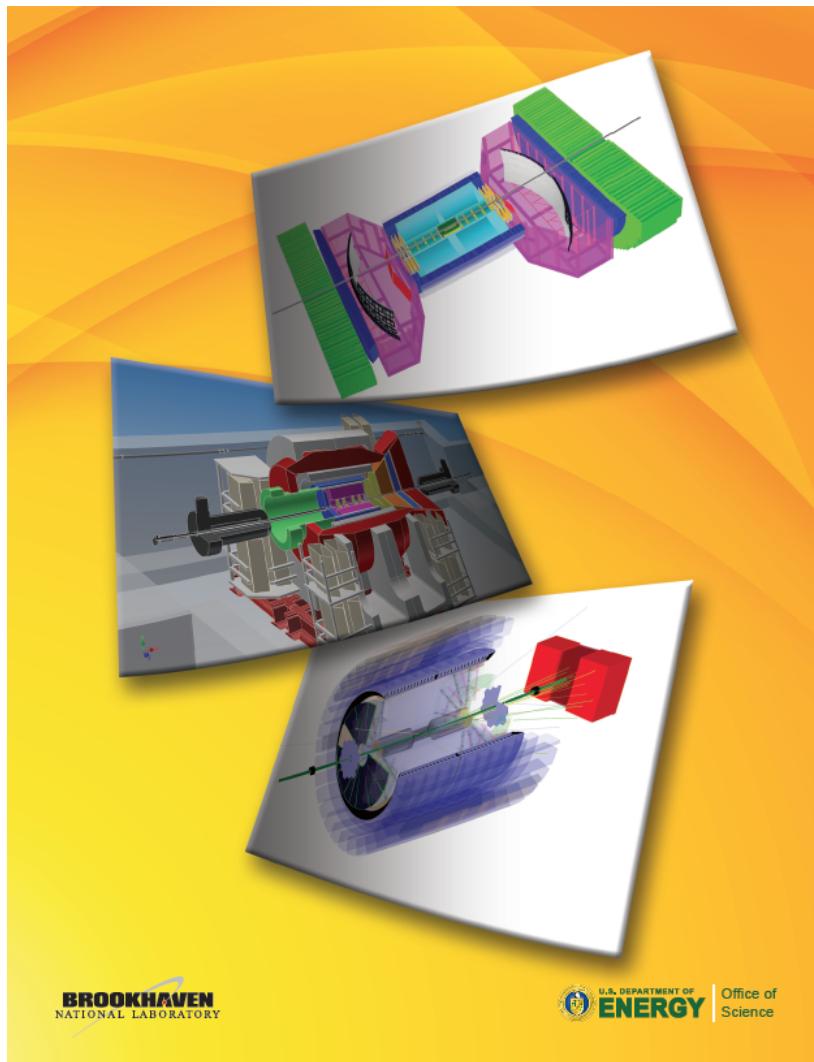
Electrons: 80%  
Protons and He3: 70%

Luminosity:

$>10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

... Still evolving

# eRHIC Detector Considerations



BeAST  
(Dedicated Detector)

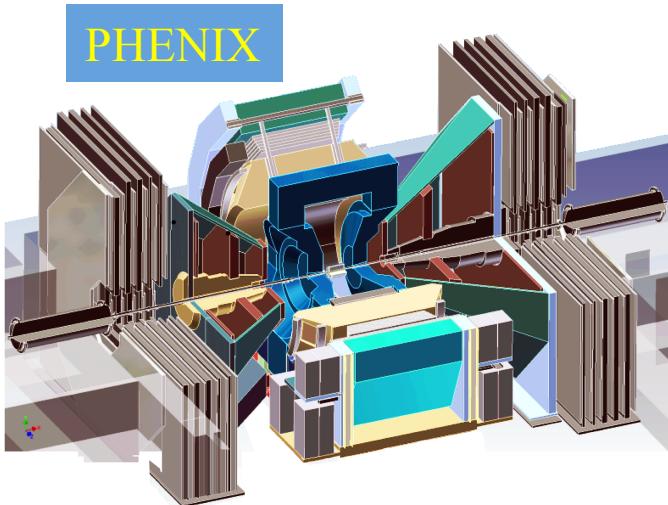
ePHENIX

eSTAR

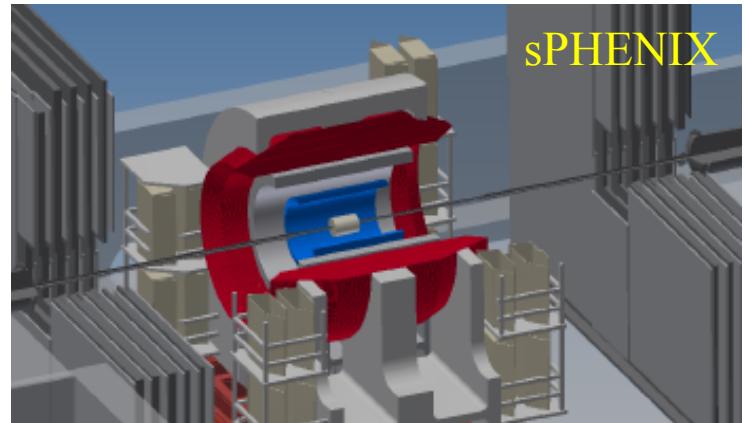
BROOKHAVEN  
NATIONAL LABORATORY

U.S. DEPARTMENT OF  
**ENERGY** | Office of  
Science

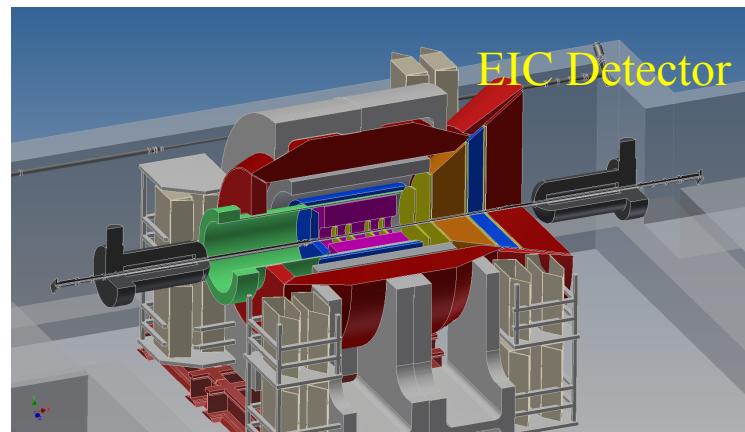
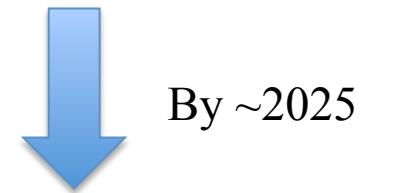
# PHENIX -> EIC Detector Path



~2021-22



By ~2025

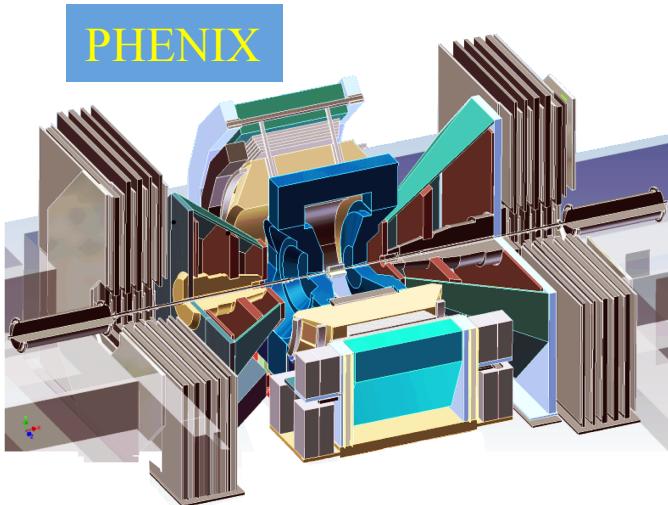


ePHENIX LoI: arXiv:1402.1209

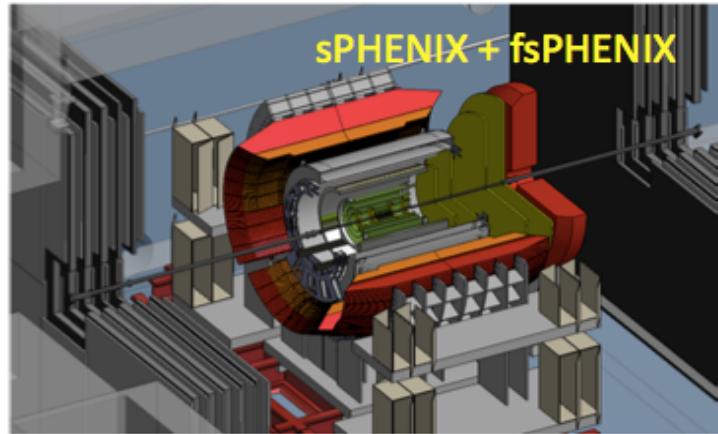
Evolve sPHENIX (pp and HI detector) to  
EIC Detector (ep and eA detector)

- To utilize e and p (A) beams at eRHIC with e-energy up to 10 GeV and  $p(A)$ -energy up to 250 GeV (100 GeV/n)
- $e, p, He3$  polarized
- Stage-1 luminosity  $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  ( $\sim 1 \text{ fb}^{-1}/\text{month}$ )

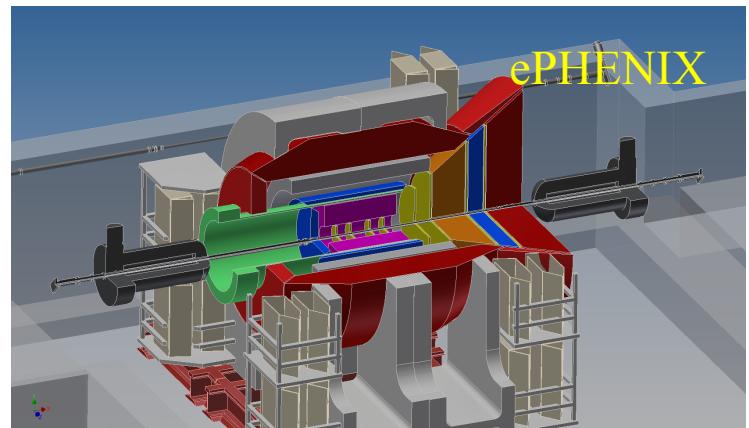
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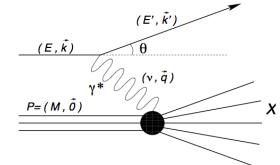
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- Stage-1 luminosity  $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  ( $\sim 1 \text{ fb}^{-1}/\text{month}$ )

# Detector Concept

## Inclusive DIS and scattered electron measurements

With focus in e-going direction and barrel

High resolution EMCAL and tracking; minimal material budget

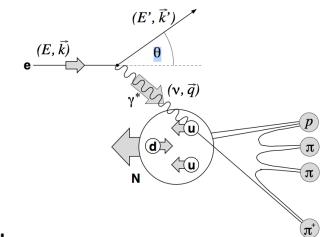


## Semi-inclusive DIS and hadron ID

With focus in h-going direction and barrel

Barrel: DIRC for  $p_h < 4$  GeV/c

h-going direction: aerogel for lower  $p_h$  and gas RICH for higher  $p_h$

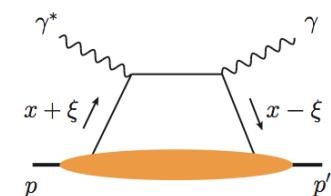


## Exclusive DIS (DVCS etc.)

EMCAL and tracking coverage in  $-4 < \eta < 4$

High granularity EMCAL in e-going direction

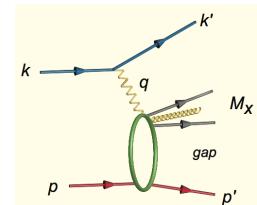
Roman Pots in h-going direction



## Diffractive

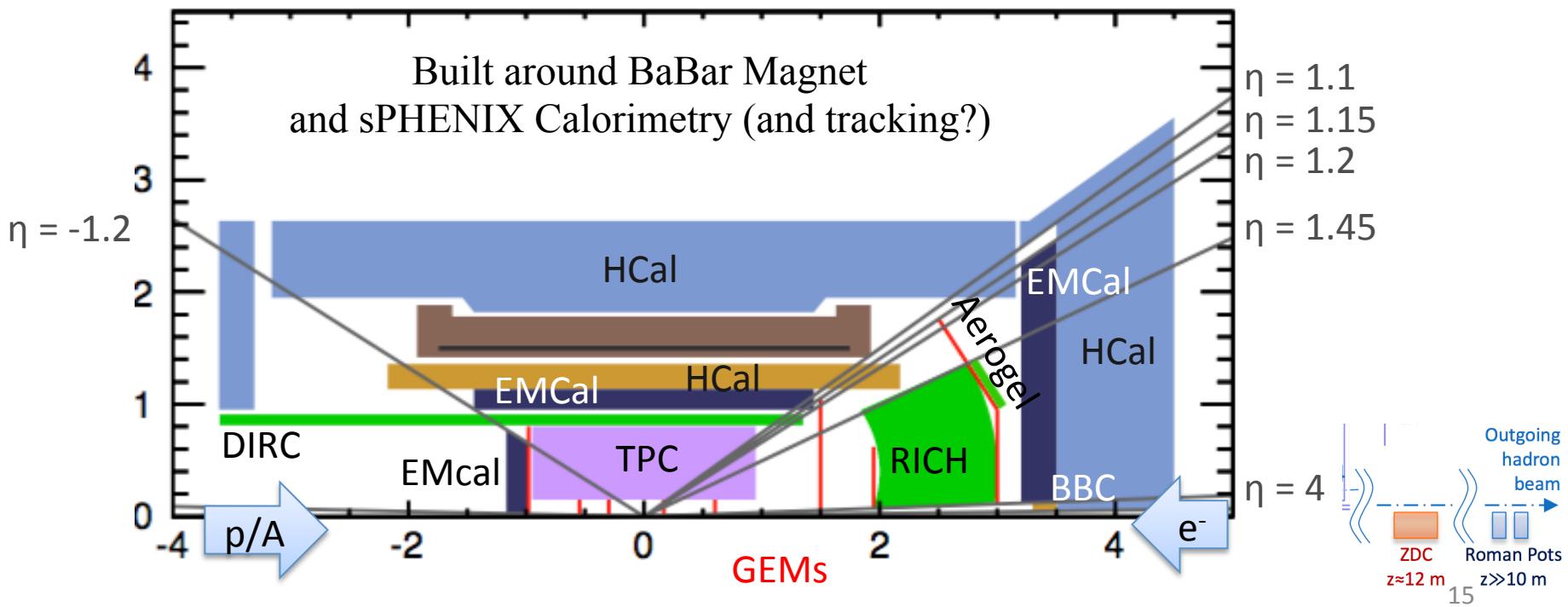
Rapidity gap measurements: HCal in  $-1 < \eta < 5$ ; EMCAL in  $-4 < \eta < 4$

ZDC in h-going direction



# Detector Concept

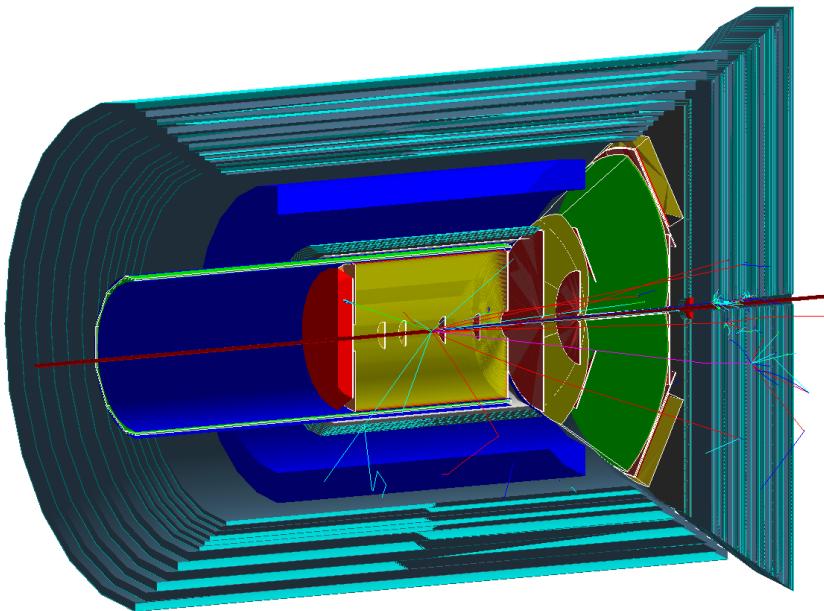
- $-4 < \eta < -1$  (e-going):
  - Crystal calorimeter with high energy and position resolution
  - GEM Trackers
- $-1 < \eta < 1$  (barrel):
  - Add Compact-TPC and DIRC
- $1 < \eta < 4$  (h-going):
  - HCal & EMCal ( $1 < \eta < 5$ )
  - GEM Trackers
  - Aerogel RICH ( $1 < \eta < 2$ )
  - Gas RICH
- Far Forward (h-going)
  - ZDC and Roman Pots



# Detector performance evaluation

## Generators:

**PYTHIA, MILOU** (for DVCS), **RAPGAP** (diffractive), **RADGEN** (rad. effects)  
Thanks to BNL EIC group for maintaining them at racf



## GEANT4 description of ePHENIX

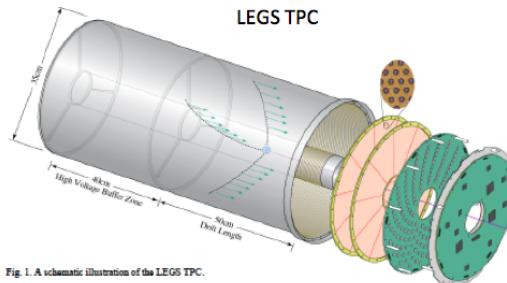
Simulation and analysis software  
common with sPHENIX

## Experience from previous DIS experiments:

**SLAC, CERN, DESY, Jlab**

Also studies and developments from **BNL EIC** group

# Magnetic Field and Tracking



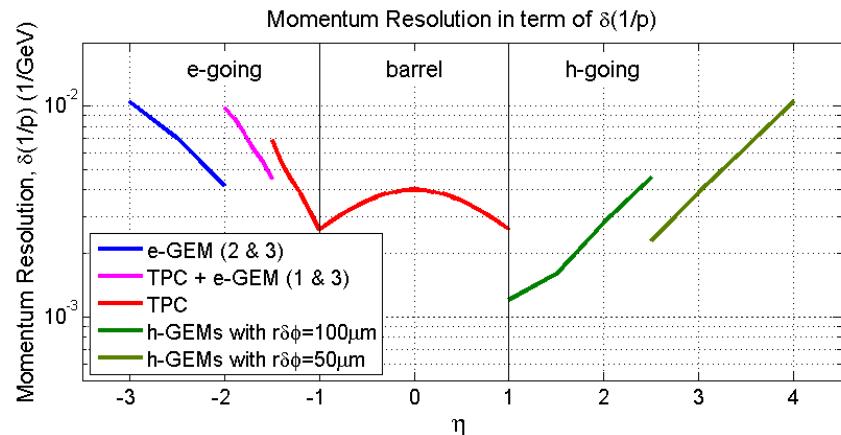
Superconducting Solenoid: 1.5 T  
Trackers (-3< $\eta$ <4):  
TPC in barrel  
GEMs in forward and backward

Good resolution over full acceptance

e-going: electron ID (E/p)

Barrel: low mom. measurements (<10 GeV/c)

h-going: needed for PID



# EM Calorimetry

$$-4 < \eta < 4$$

Endcap EMCal:

$$\sigma_E/E \sim 1.5\%/\sqrt{E}$$

$$\sigma_X < 3\text{mm}/\sqrt{E}$$

PbWO<sub>4</sub> crystal

Similar to PANDA  
endcap design

Barrel EMCal:

$$\sigma_E/E \sim 12\%/\sqrt{E}$$

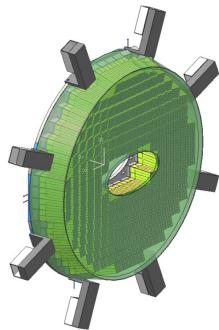
sPHENIX EMCal

Tungsten-fiber

Forward EMCal:

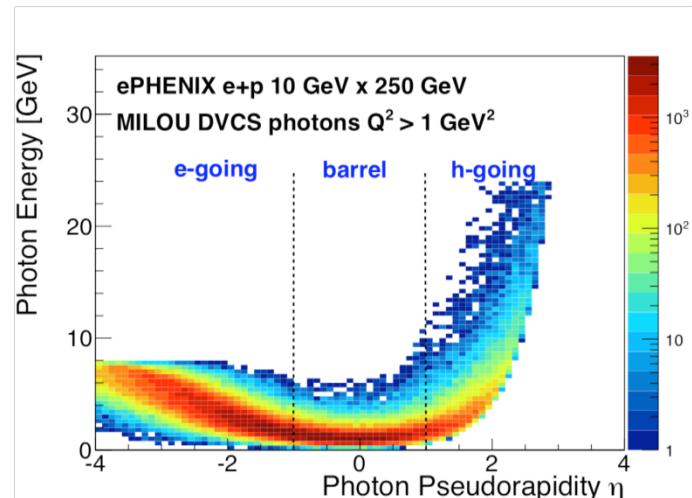
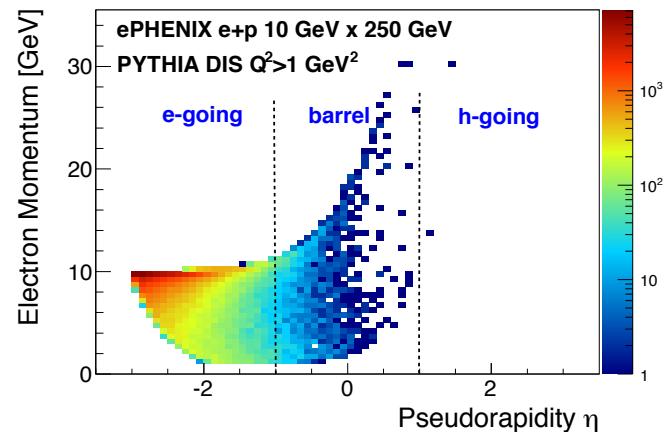
$$\sigma_E/E \sim 12\%/\sqrt{E}$$

Pb-fiber



TDR for PANDA  
arXiv:0810.1216

- Scattered electron measurements
  - High resolutions in e-going direction required
- Vector meson and photon measurements
  - Wide coverage required



# Hadron Calorimetry

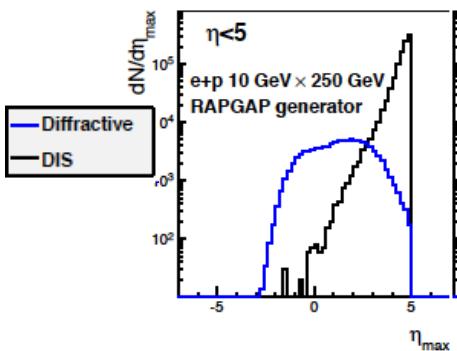
$$-1 < \eta < 5$$

Barrel HCal:

$$\sigma_E/E \sim 100\%/\sqrt{E}$$

Steel & Scintillator

sPHENIX EMCal

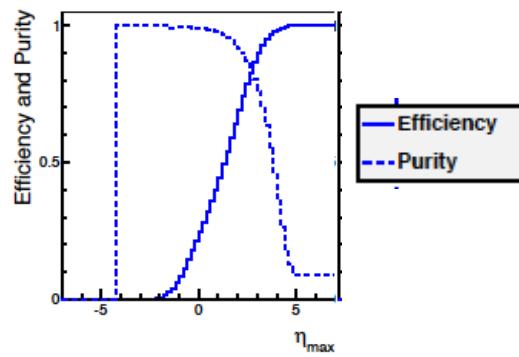


Forward HCal:

$$\sigma_E/E \sim 100\%/\sqrt{E}$$

Steel & Scintillator

Same as barrel



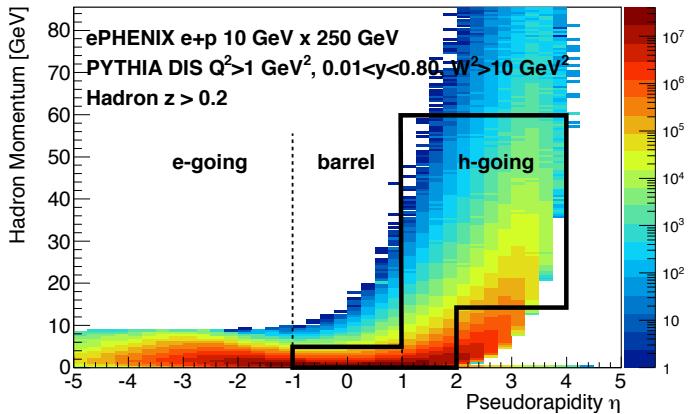
sPHENIX prototype



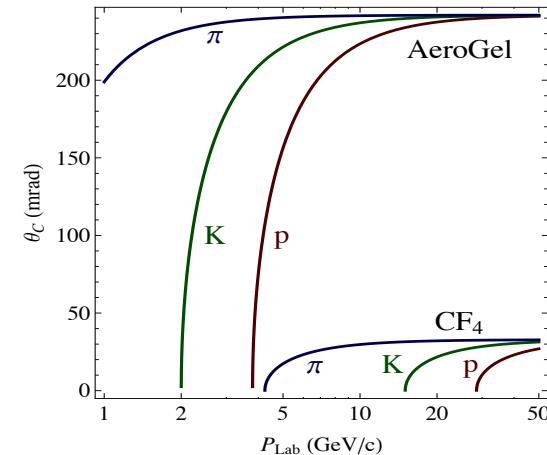
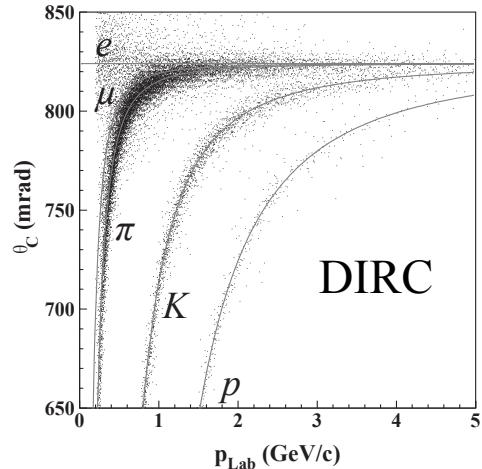
- Rapidity Gap for Diffractive
- Assist to PID and high momentum hadron measurements

# Hadron PID

$$-1 < \eta < 4$$



Focus on h-going direction and barrel



DIRC:

$$-1 < \eta < 1$$

PID at  $< 4 \text{ GeV}/c$

Aerogel:

$$1 < \eta < 2$$

PID at  $< 15 \text{ GeV}/c$

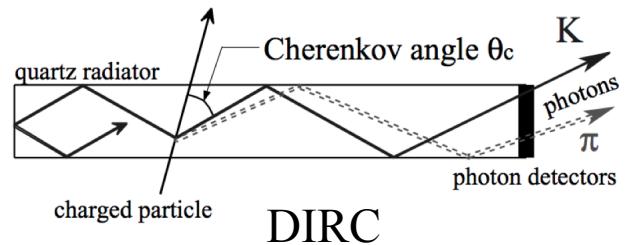
Gas RICH (CF4):

$$1 < \eta < 4$$

PID at  $< 60 \text{ GeV}/c$

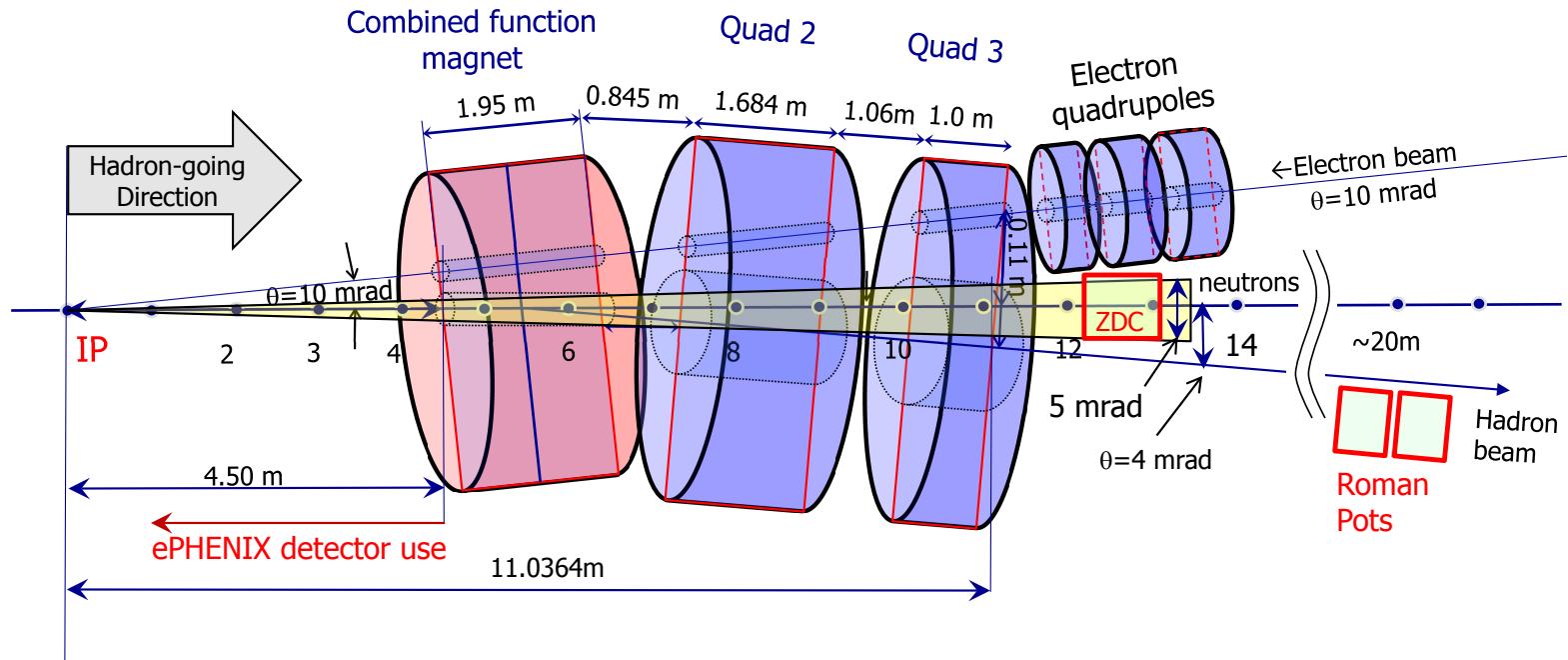
➤ Quark Helicity, TMDs, Hadronization

Tightly coupled to high resolution momentum measurements in forward rapidity



# Beamline Detectors

Similar to all eRHIC detectors, being designed in parallel with IR design



## ZDC

12 m downstream

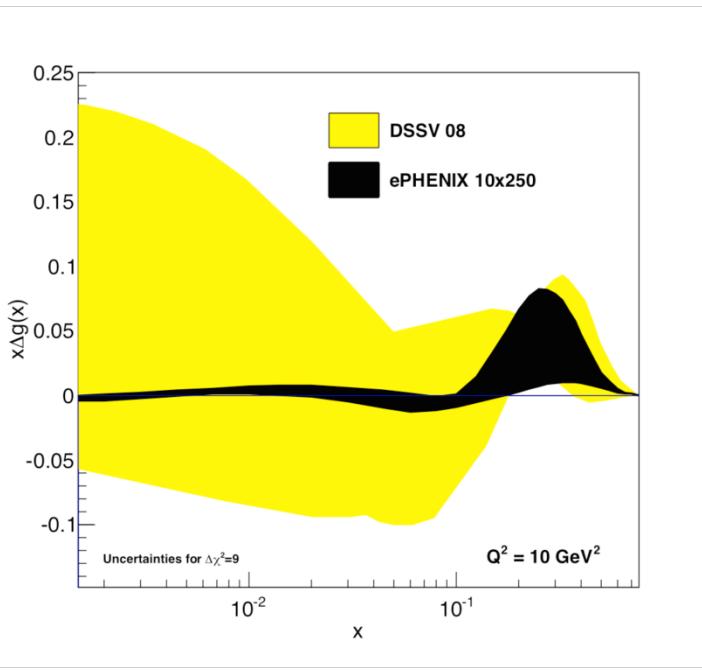
5 mrad cone opening of the IP is available from ePHENIX and IP design

## Roman Pots

>20 m downstream

Similar to STAR design

# Physics Expectations: Quick exercises with ‘ePHENIX’

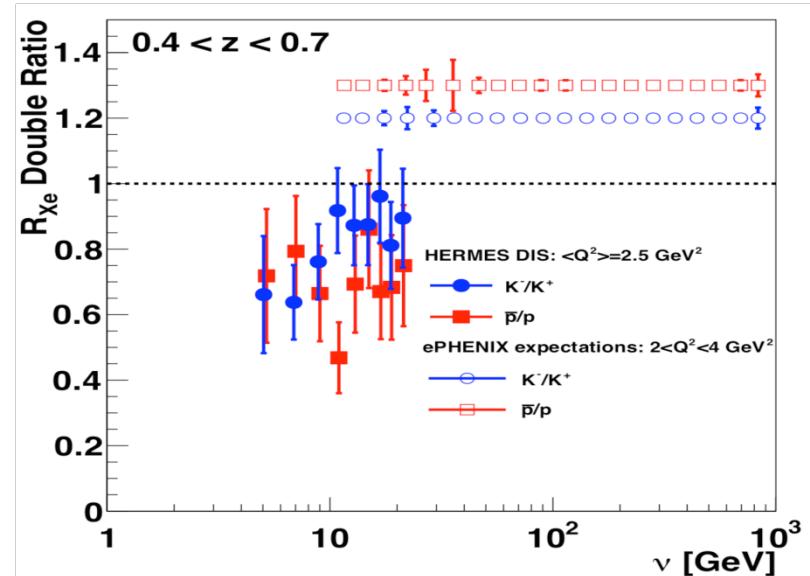


Parton hadronization –  
modified fragmentation

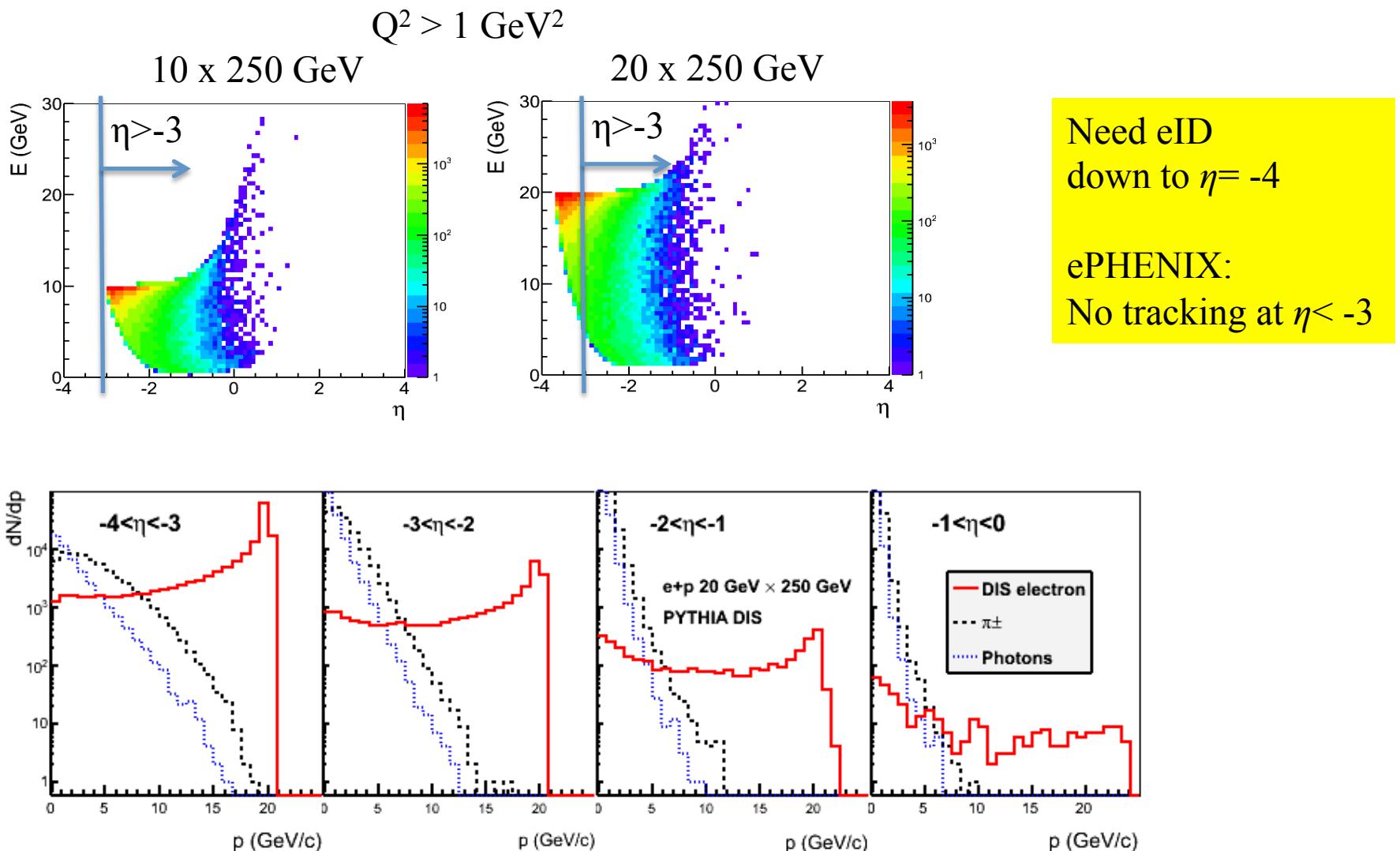
$2 < Q^2 < 4 \text{ GeV}^2$

$2 \text{ fb}^{-1}$  at  $5\text{GeV} \times 250\text{GeV}$

$\Delta g(x)$  from long. pol. ep:  
PHYTHIA generator and ePHENIX  
acceptance/efficiencies  
 $10 \text{ fb}^{-1}$  at  $10\text{GeV} \times 250\text{GeV}$

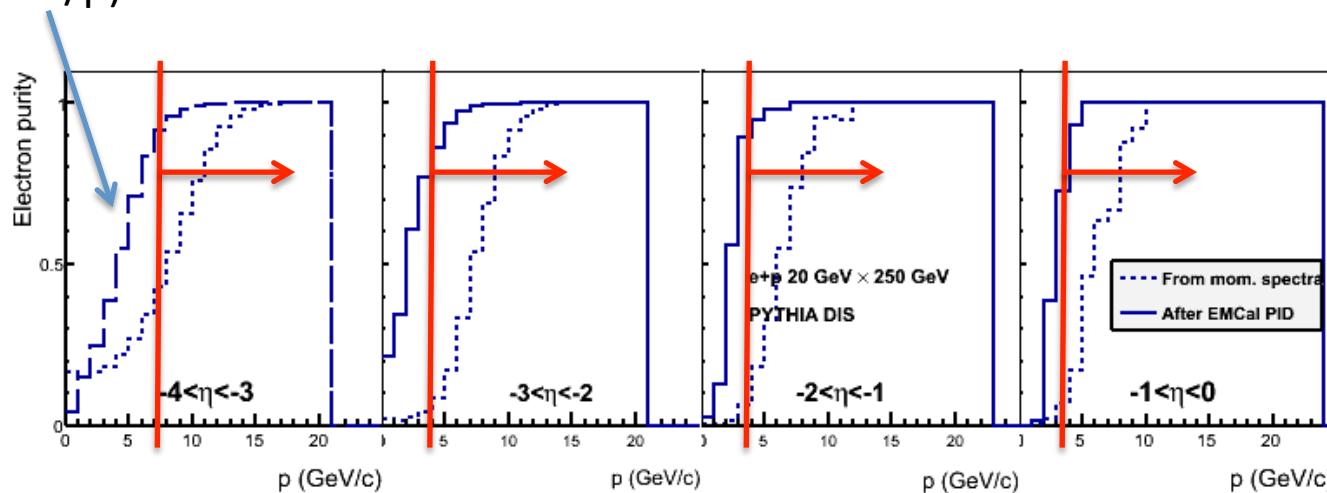


# From 10 GeV to 20 GeV e beam



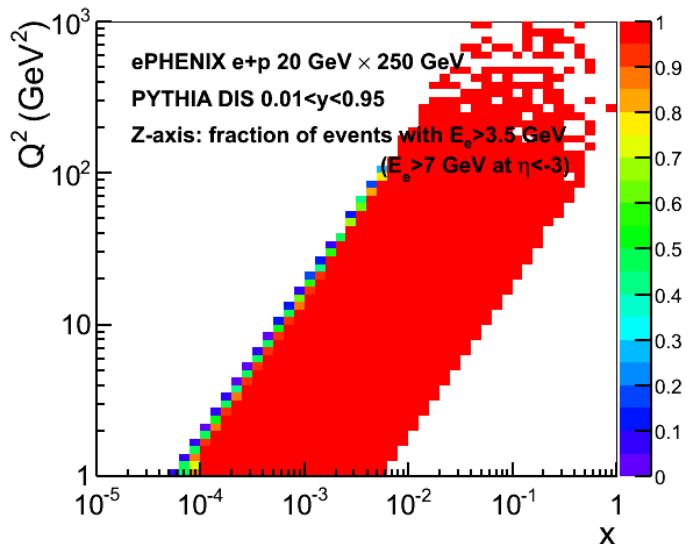
# 20x250 GeV: eID purity

No tracking  
(no E/p)



eID: EMCAL response  
and E/p

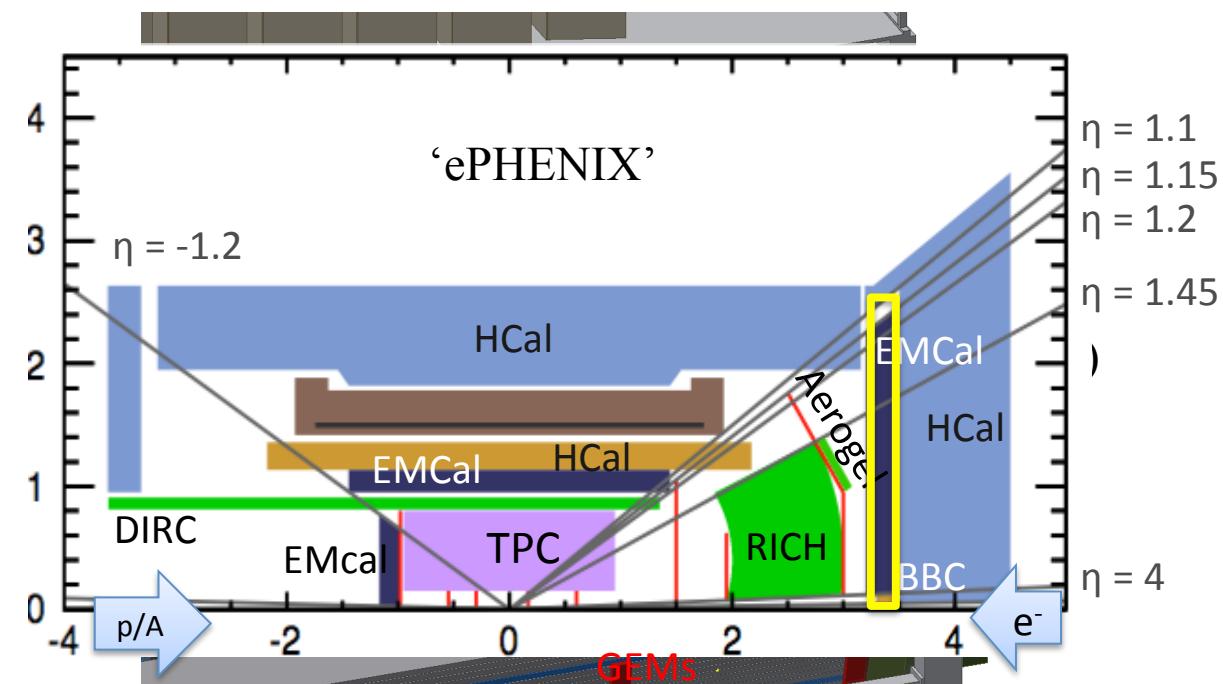
EMCal shower profile  
may give another factor  
3-10



Don't lose much of  
the  $(x, Q^2)$  space  
Even with no tracking at  
 $\eta < -3$  (charged veto still  
needed for photon rejection)

# sPHENIX + fsPHENIX → ePHENIX

- Make sure s(f)PHENIX concept is consistent with ePHENIX plans
- fsPHENIX = sPHENIX +
  - PHENIX reconfigured: forward Si tracker, Muon ID (and EMCal?)
  - EIC Detector forward systems: GEMs and HCal
  - 90% of the cost common with EIC detector



In current sPHENIX design:  
Plug door (flux return) at 3.3m  
Could we move EMCal towards IR?  
Will 20-30cm of iron deteriorate  
HCal measurements?  
Don't see principle limitations, but  
need simulation

# ePHENIX Concept Review (Jan 10, 2014)

## Review Committee:

Sam Aronson (BNL); Krishna Kumar (UMass-Amherst); Jianwei Qiu(BNL); Veljko Radeka(BNL); Paul E. Reimer (ANL); Jim Thomas (LBNL); Glenn Young (Jlab)

The review team was unanimous in its praise for the LOI

This approach allows for a cost-effective way of providing the capability to address the physics agenda of eRHIC from Day-1 of eRHIC operation

Very reasonable balance between using existing components and a completely new detector

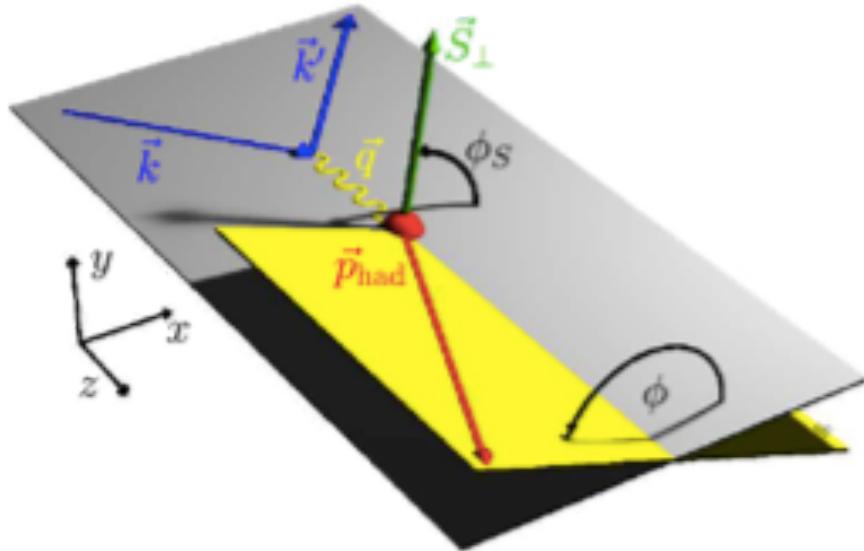
Well demonstrated that ePHENIX would be a good day-one detector capable of addressing almost all of the physics that can be covered by eRHIC

A solid foundation for future upgrades so that it can explore the full physics potentials available as eRHIC itself evolves

# Summary

# Backup

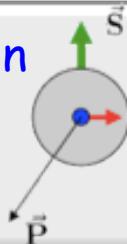
# SIDIS



$$\frac{d\sigma}{dx dQ^2 dz d\phi_s d\phi_h dp_T^h}$$

Sivers function

$\sin(\phi_h - \phi_s)$   
modulation



correlation of nucleon's transverse spin

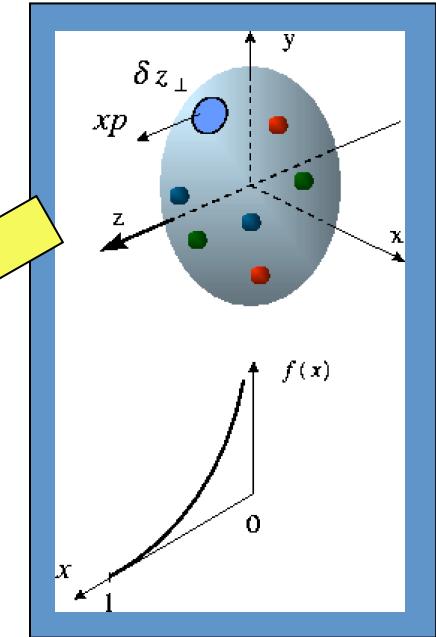
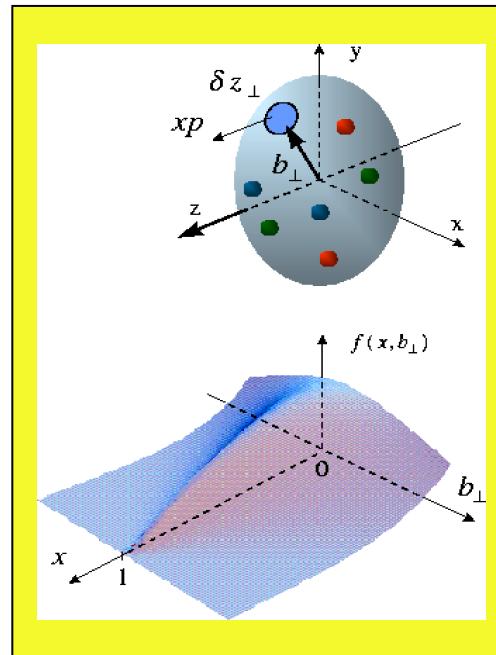
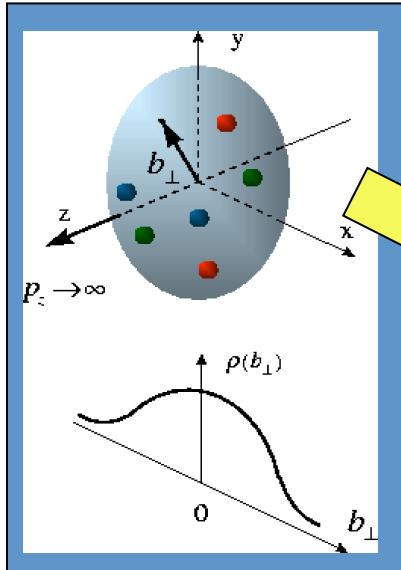
with the  $k_T$  of an unpolarized quark

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

# Generalized Parton Distributions

Beyond form factors and PDFs

X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors,  
transverse charge &  
current densities

Correlated quark momentum  
and helicity distributions in  
transverse space - GPDs

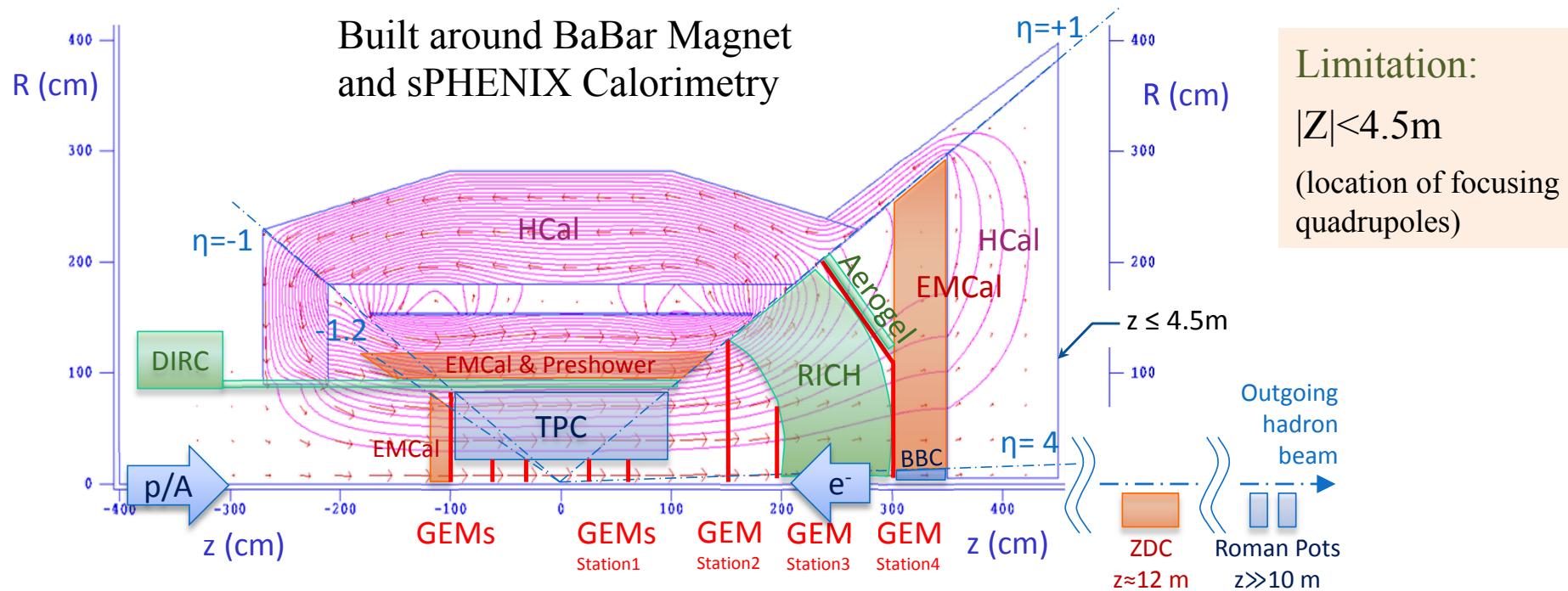
Structure functions,  
quark longitudinal  
momentum & helicity  
distributions

the way to 3d imaging of the proton and the orbital angular momentum  $L_q$  &  $L_g$

Constrained through exclusive reactions

# Detector Concept

Built around BaBar Magnet  
and sPHENIX Calorimetry



- $-4 < \eta < -1$  (e-going):
  - Crystal calorimeter with high energy and position resolution
  - GEM Trackers
- $-1 < \eta < 1$  (barrel):
  - Add Compact-TPC and DIRC
- $1 < \eta < 4$  (h-going):
  - HCAL & EMCAL ( $1 < \eta < 5$ )
  - GEM Trackers
  - Aerogel RICH ( $1 < \eta < 2$ )
  - Gas RICH
- Far Forward (h-going)
  - ZDC and Roman Pots

# BaBar Magnet



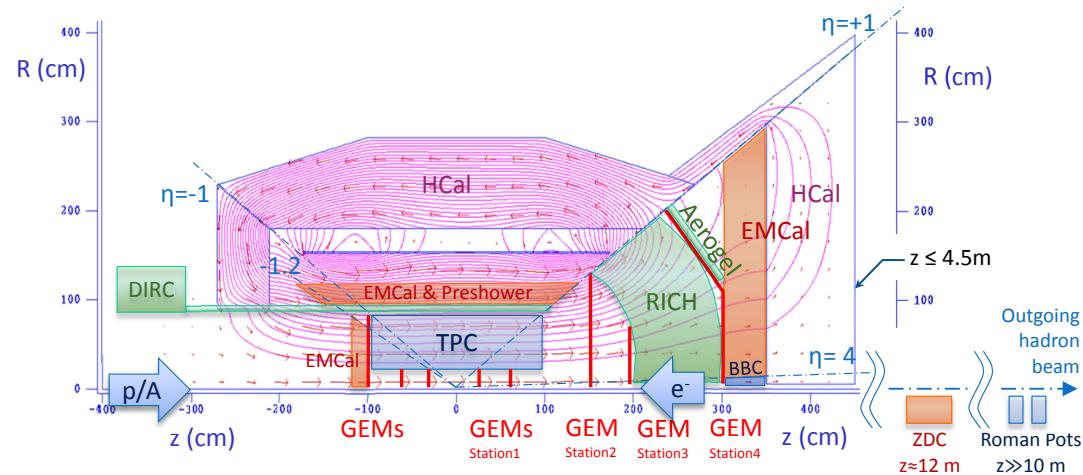
Higher current density at magnet ends and field shaping in forward angles provide **high analyzing power** for momentum determination in e-going and h-going directions

Flux return and field shaping:

- Forward HCal
- Steel lapmshade
- Barrel HCal
- Steel endcup

## Major Parameters:

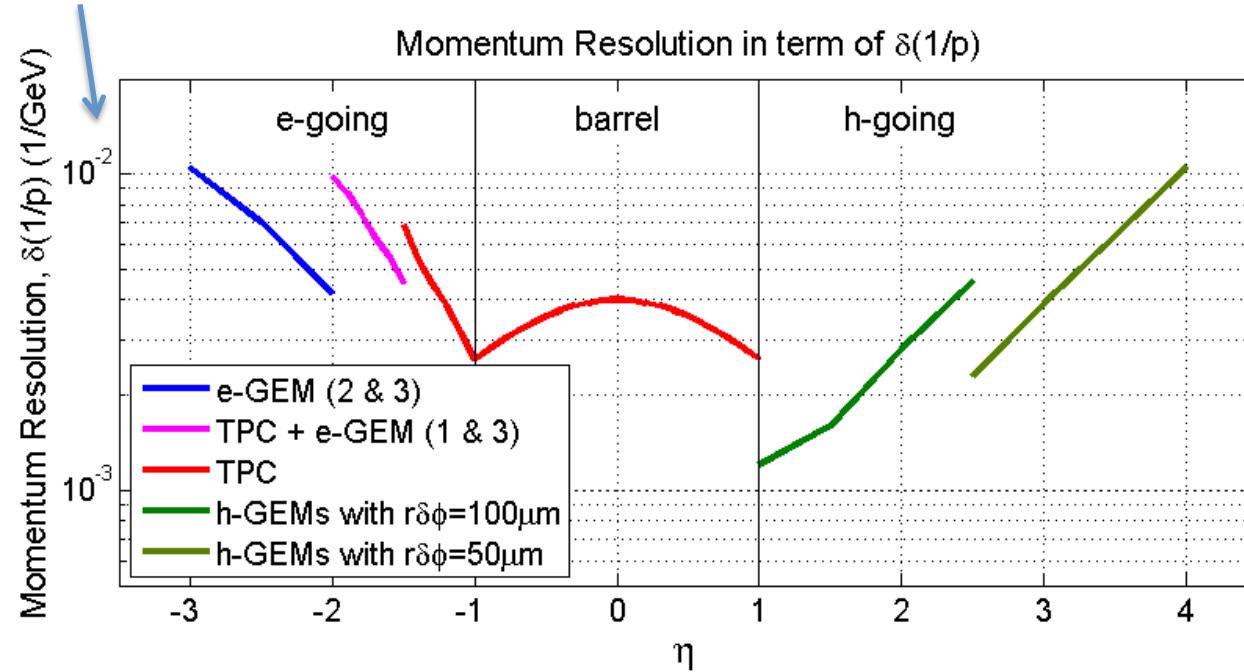
- ✓ Superconducting Solenoid
- ✓ Field: 1.5T
- ✓ Inner radius: 140 cm
- ✓ Outer radius: 173 cm
- ✓ Length: 385 cm



Main space limitation observed:  $|z| < 4.5\text{m}$   
(due to focusing magnet location)

# Momentum Resolution

$$\delta p/p \sim a \times p$$

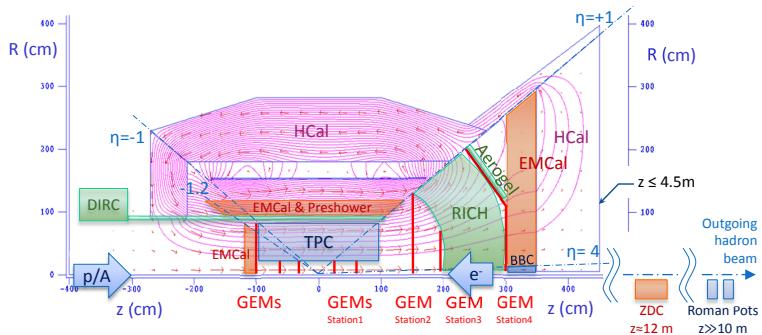
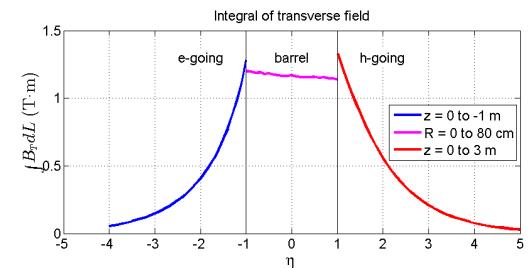


Good resolution over full tracking acceptance ( $-3 < \eta < 4$ ):

e-going,  $\sigma_p/p \sim (0.4-1.0\%) \times p$ : primarily needed for electron ID (E/p)

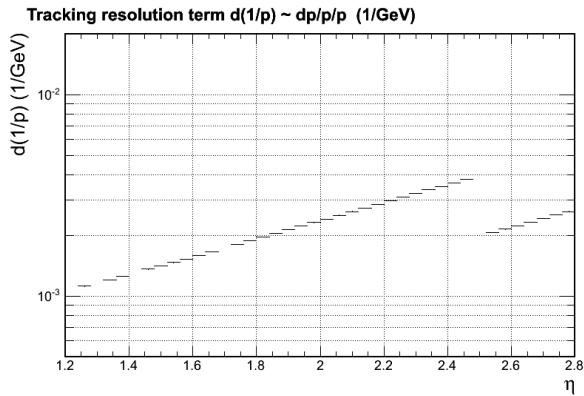
barrel,  $\sigma_p/p < 0.4\% \times p$ : hadron momentum, electron momentum at  $p < 10 \text{ GeV}/c$

h-going,  $\sigma_p/p \sim (0.1-1.0\%) \times p$ : crucial for PID

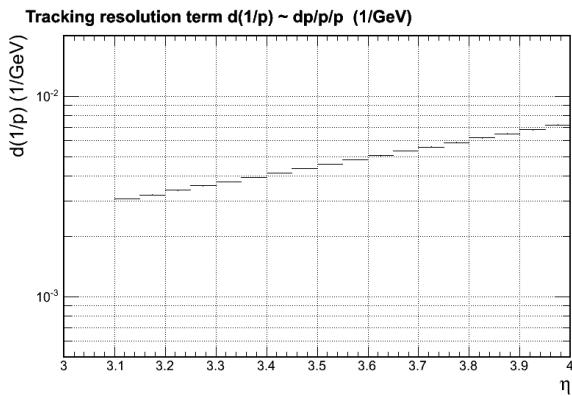


# Momentum resolution: GEANT4

$1 < \eta < 3$

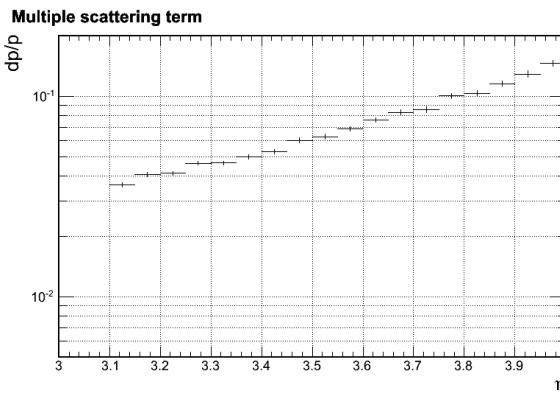
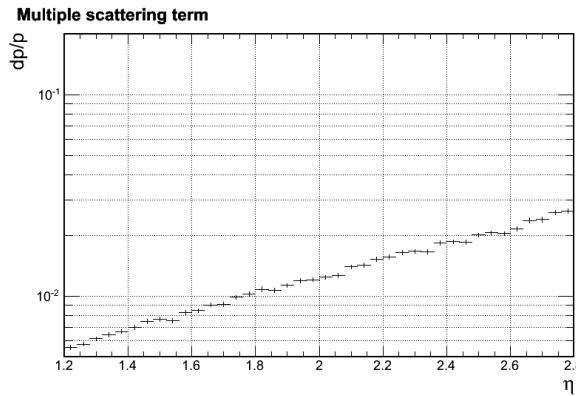


$3 < \eta < 4$



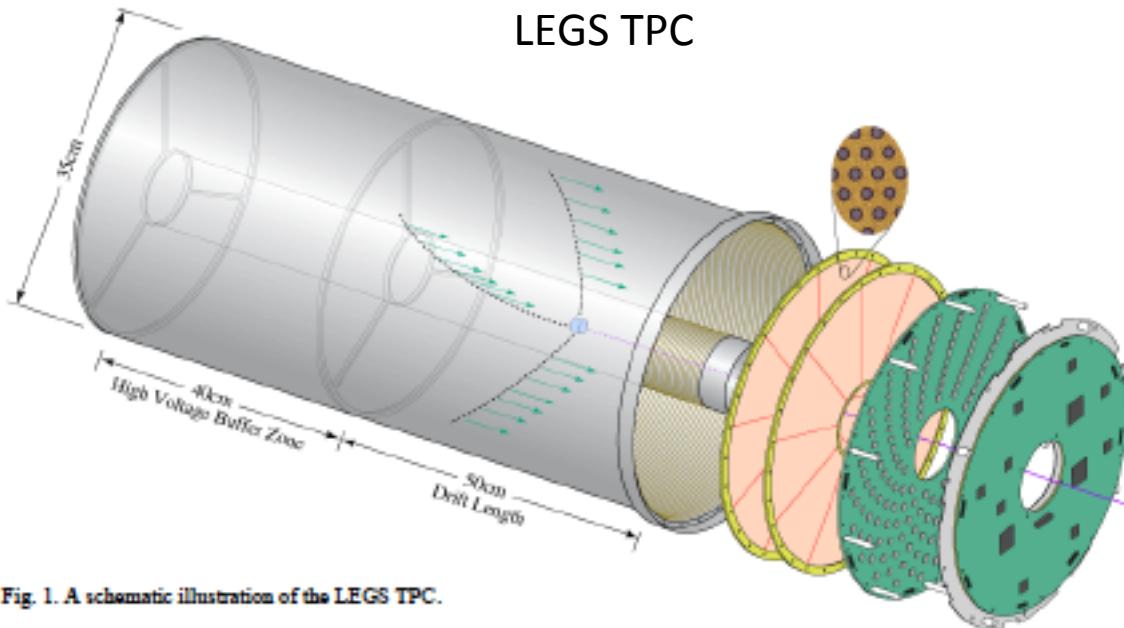
Tracker resolution term,  
assuming fixed resolution on sagitta:

$1 < \eta < 2.5$ :  $d(\text{Sagitta}_2) = 120\mu\text{m}$  for  $100\mu\text{m}$  tracker resolution  
 $2.5 < \eta < 4$ :  $d(\text{Sagitta}_2) = 60\mu\text{m}$  for  $50\mu\text{m}$  tracker resolution



Multiple scattering term  
Without RICH

# TPC



Chevron-type readout pattern  
with a pad size 2mm × 5mm

Achieved pos. res. 200 μm

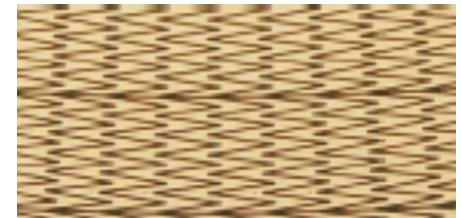


Fig. 1. A schematic illustration of the LEGS TPC.

## ePHENIX TPC:

R=15-80cm, |z|<95cm

Gas mixture with fast drift time: 80% Ar, 10% CF<sub>4</sub>, 10% CO<sub>2</sub>

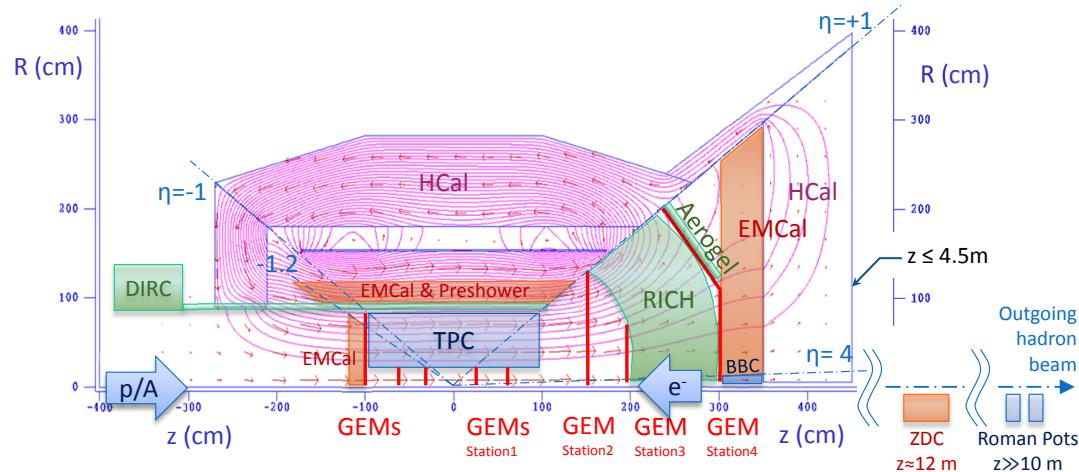
For 650 V/m → 10cm/μs → Drift time 10 μs

2×10mm pads → 180k pads (both ends readout)

Pos. resolution 300 μm (twice longer drift distance than LEGS)  
and 40 readout rows =>  $\sigma_p/p \sim 0.4\% \times p$

# Tracking with GEM

Improved pos. res.  
with mini-drift GEM



## e-going direction

Station 1-2:  $z=30, 55$  cm  $r=2-15$  cm

Station 3:  $z=98$  cm

$-3 < \eta < -2$ :  $50\mu\text{m}$  with 1mm pad

$-2 < \eta < -1$ :  $100\mu\text{m}$  with 2mm pad

$\Delta r = 1$  cm for St1-2 and  $\Delta r = 10$  cm for St3

## h-going direction

Station 1:  $z=17$  and  $60$  cm with  $r=2-15$  cm

Station 2-4:  $z=150, 200, 300$  cm,  $1 < \eta < 4$

$2.5 < \eta < 4$ :  $50\mu\text{m}$  with 1mm pad

$1 < \eta < 2.5$ :  $100\mu\text{m}$  with 2mm pad

$\Delta r = 1-10$  cm

Collision vertex is necessary in e-going direction:

BBC:  $\eta=4-5$ ,  $z=3$  m,  $\sigma_t=30$  ps (with MRPC or MCP) ->  
 $\sigma_z=5$  mm -> const term in  $\sigma_p/p \sim 2\%$

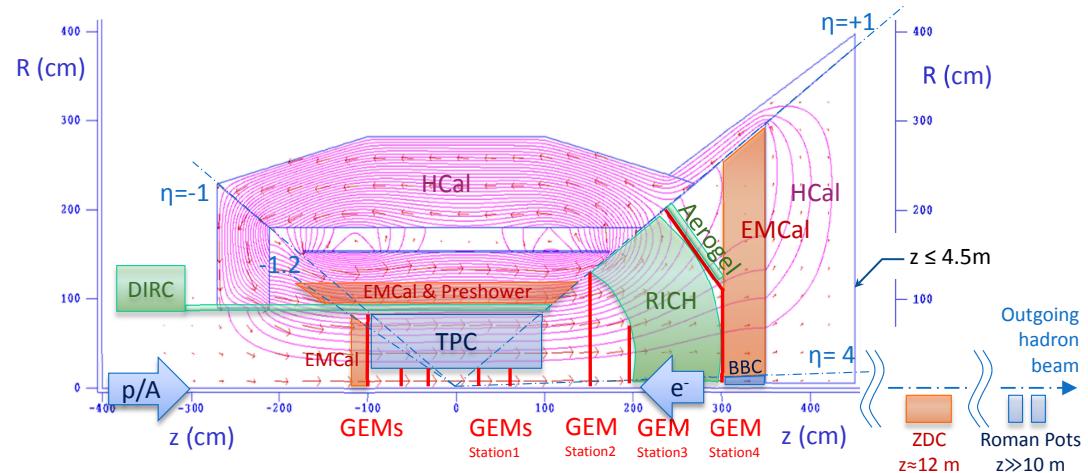
Total channel count: 217k

Large area GEMs are being developed in CERN for CMS  
 (needed for our St 2-4)

# Calorimetry

EMCal coverage  $-4 < \eta < 4$   
 HCal coverage  $-1 < \eta < 5$

Readout: SiPM



## e-going direction

### Crystall EMCal:

$2\text{cm} \times 2\text{cm}$

5k towers

$\sigma_E/E \sim 1.5\%/\sqrt{E}$

$\sigma_x \sim 3\text{mm}/\sqrt{E}$

## Barrel (sPHENIX)

### Tungsten-fiber EMCal:

$2\text{cm} \times 2\text{cm}$

25k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

### Steel-Sc HCal:

$10\text{cm} \times 10\text{cm}$

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

## h-going direction

### Pb-fiber EMCal:

$3\text{cm} \times 3\text{cm}$

26k towers

$\sigma_E/E \sim 12\%/\sqrt{E}$

### Steel-Sc HCal:

$10\text{cm} \times 10\text{cm}$

3k towers

$\sigma_E/E \sim 100\%/\sqrt{E}$

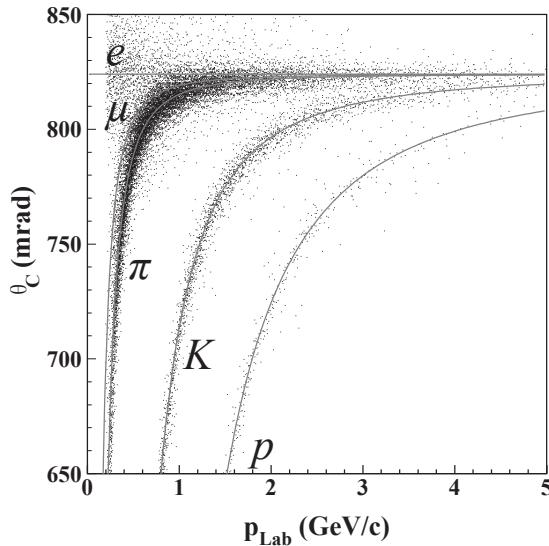
# Hadron PID

## DIRC

$-1 < \eta < 1$

Mirror focusing

Threshold for  $\pi/K/p$ :  
0.2/0.7/1.5 GeV



## Gas RICH (CF4)

$1 < \eta < 4$

Mirror focusing

Threshold for  $\pi/K/p$ :  
4/15/29 GeV

6 azimuthal segments  
Photodetection: GEM with CsI

Area  $6 \times 0.3 \text{ m}^2 \rightarrow 96 \text{ k ch}$

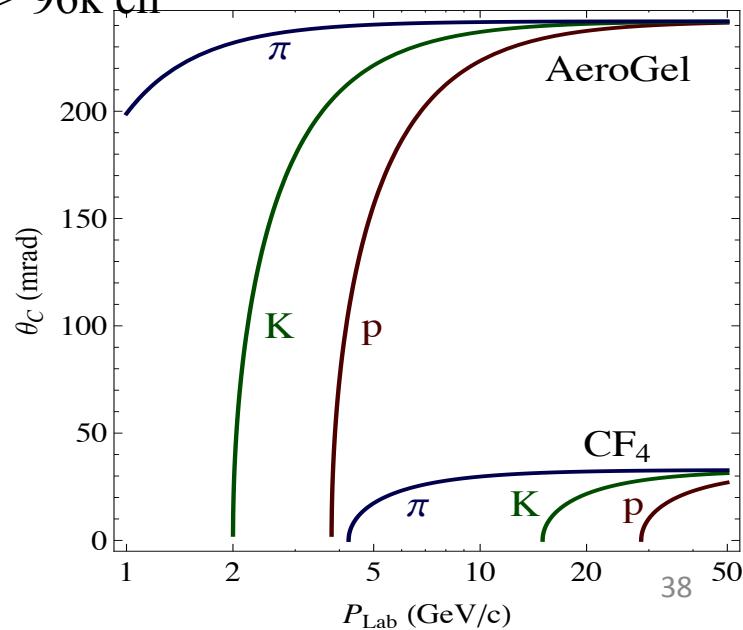
In gas volume!

## Aerogel

$1 < \eta < 2$

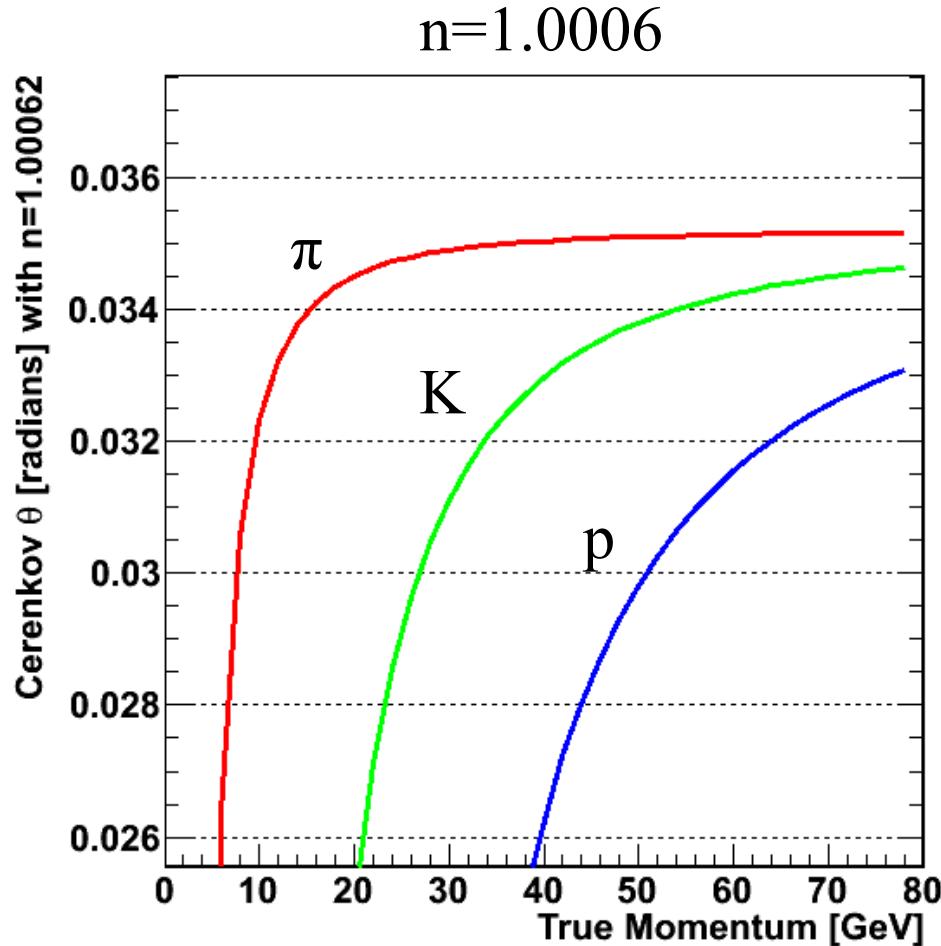
Proximity focused

Threshold for  $\pi/K/p$ :  
0.6/2/4 GeV

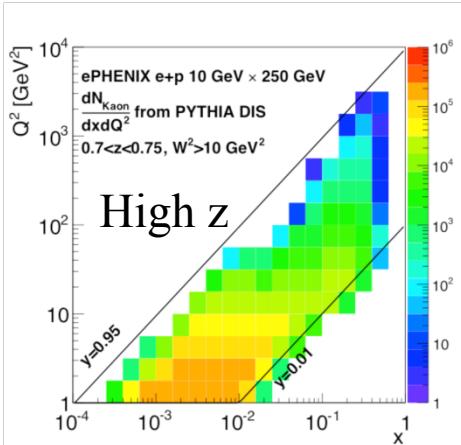
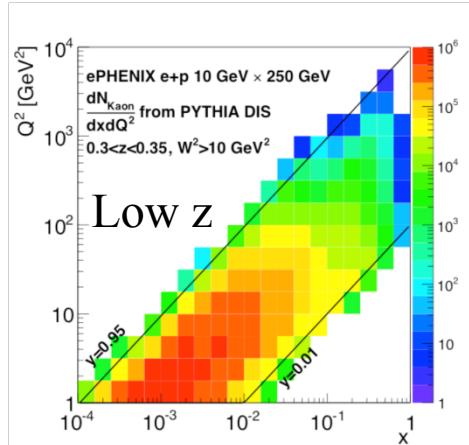


$P_{\text{Lab}}$  (GeV/c)

# Cerenkov Angle in CF4



# Semi-inclusive DIS and hadron ID

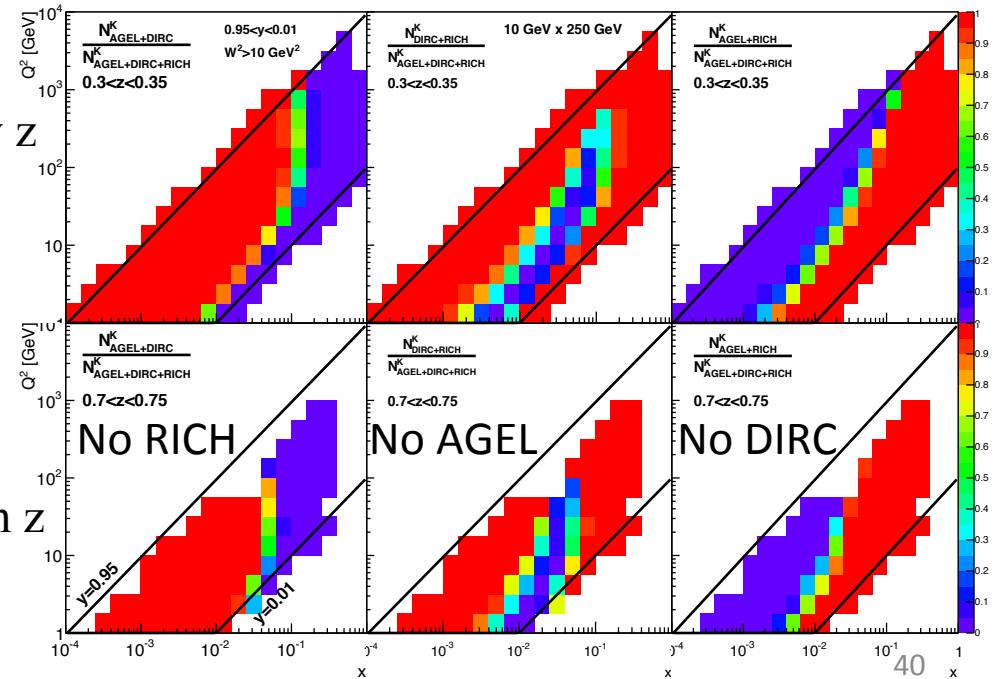


$(x, Q^2)$  coverage with K

$(x, Q^2)$  loss if not have given detector



Low Z



All three detectors are important

# Hadron PID: gas RICH

CF4 ( $n=1.00062$ )

## Ring resolution

Ring radius resolution:  $2.5\%/\sqrt{N_\gamma}$

From current EIC R&D studies

LHCb and COMPASS claimed 1% per photon

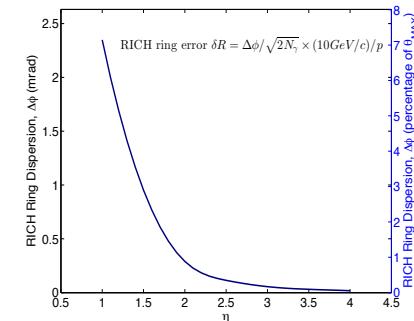
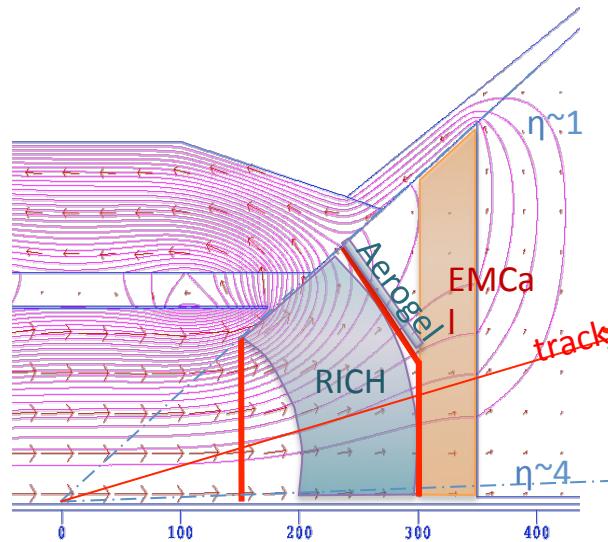
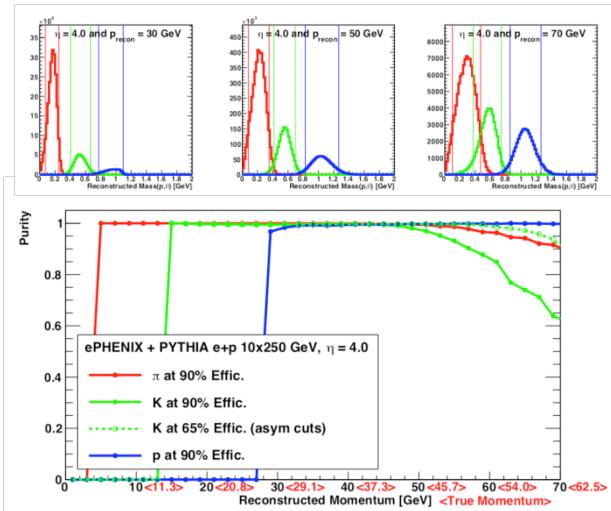
Residual magnetic field ( $\sim 0.5$  T)  
bends tracks radiating photons  $\Rightarrow$  ring smearing

Since field is near parallel to tracks  
the effect is minimal

Off-center vertex tracks have shifted focal plane  $\Rightarrow$  ring smearing

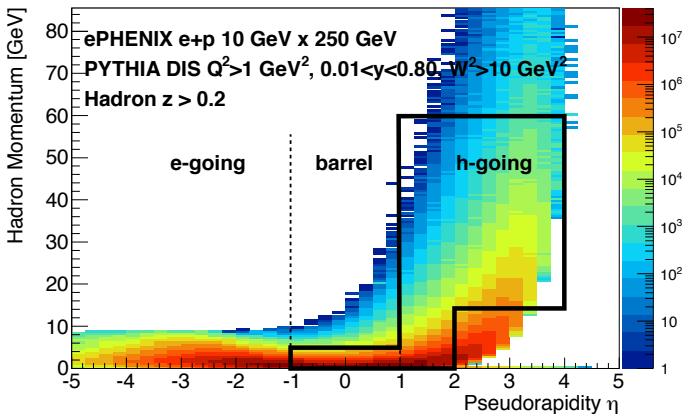
For  $\eta=1$  and  $z=40\text{cm} \Rightarrow$  ring dispersion  $5\%/\sqrt{N_\gamma} \times (10\text{ GeV}/c) / p$

For larger  $\eta$  effect is smaller



Ring resolution limits PID at higher  $p$

# Hadron PID: gas RICH

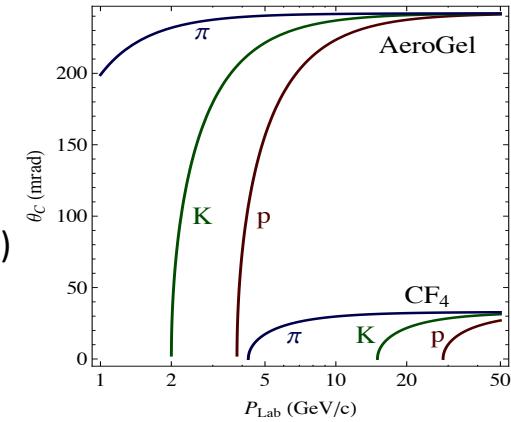


Gas RICH (CF4):  $1 < \eta < 4$

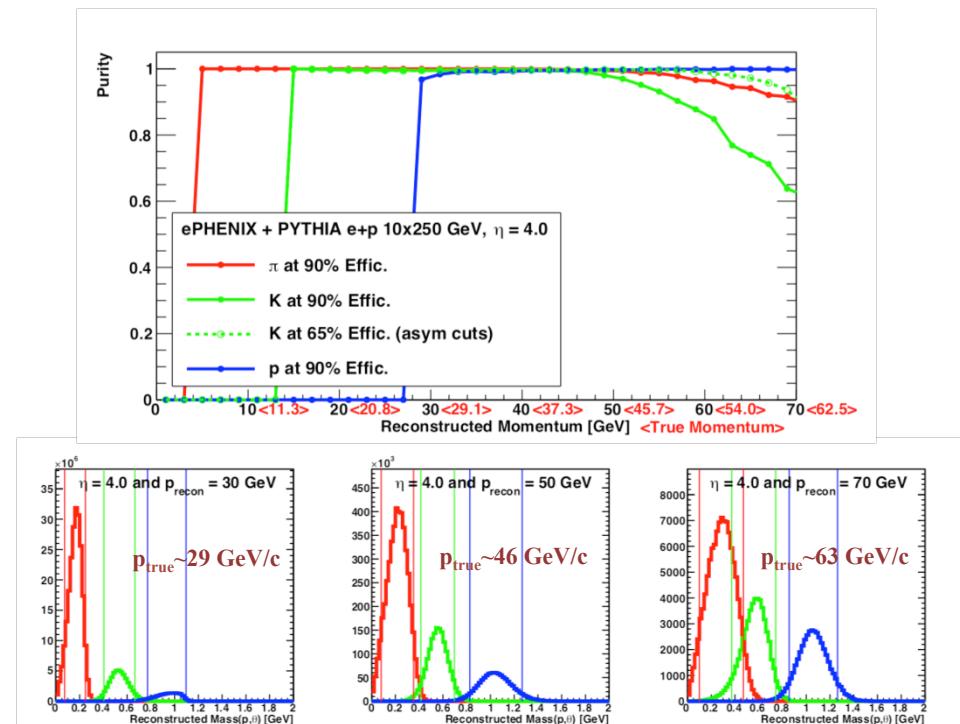
Highest momentum measurements require:

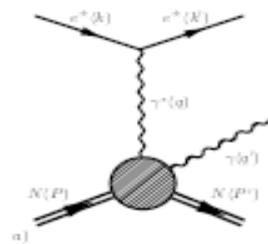
- Good momentum resolution (combination of tracking and HCal)
- Good ring resolution

Need to balance efficiency and purity to get best measurement



- PID up to  $\sim 60$  GeV/c
- Currently limited by ring resolution (2.5% per photon - the current feedback from EIC R&D)
- Much smaller smearing due to magnetic field and off-center-vertex tracks





# Exclusive Measurements

## DVCS:

Wide coverage for photon measurements

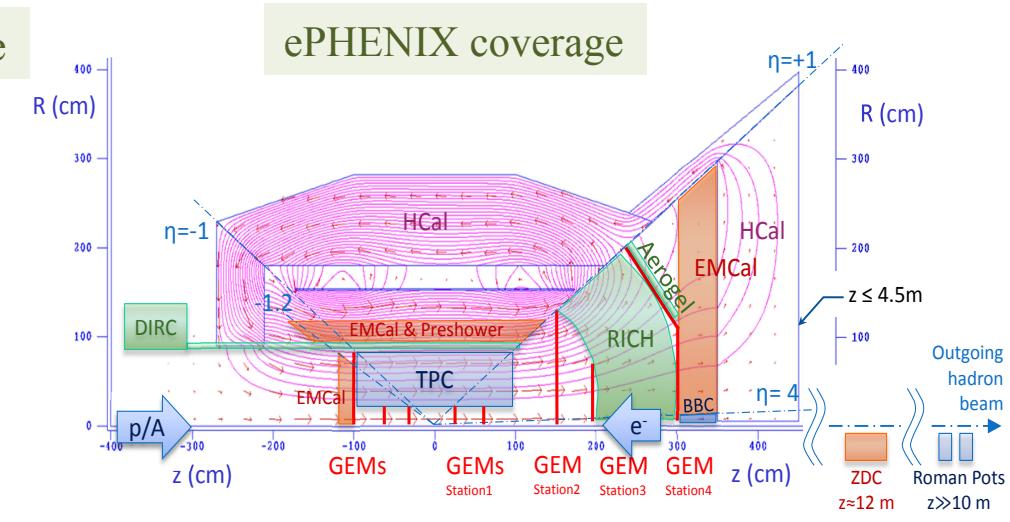
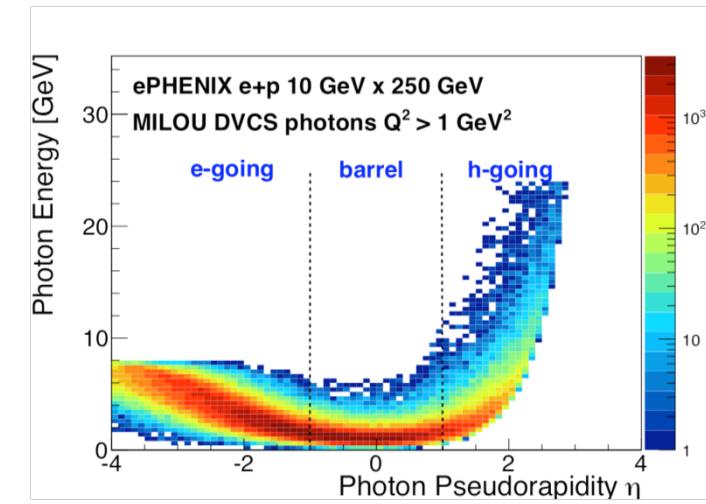
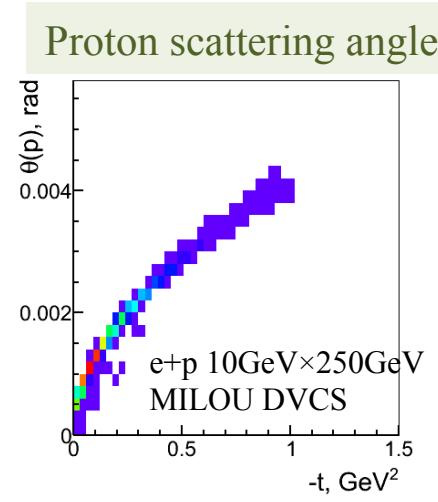
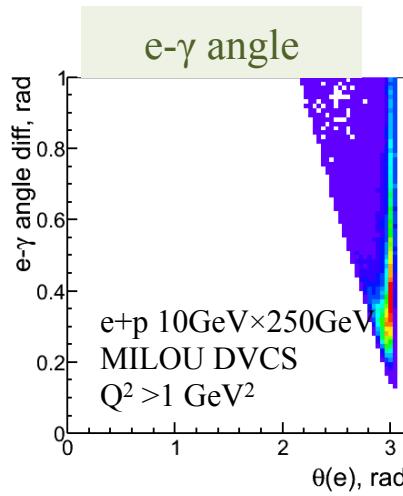
EMCal and tracking in  $|\eta| < 4$

Separation of e- $\gamma$  in EMCal

$0.02 \times 0.02$  EMCal granularity is sufficient

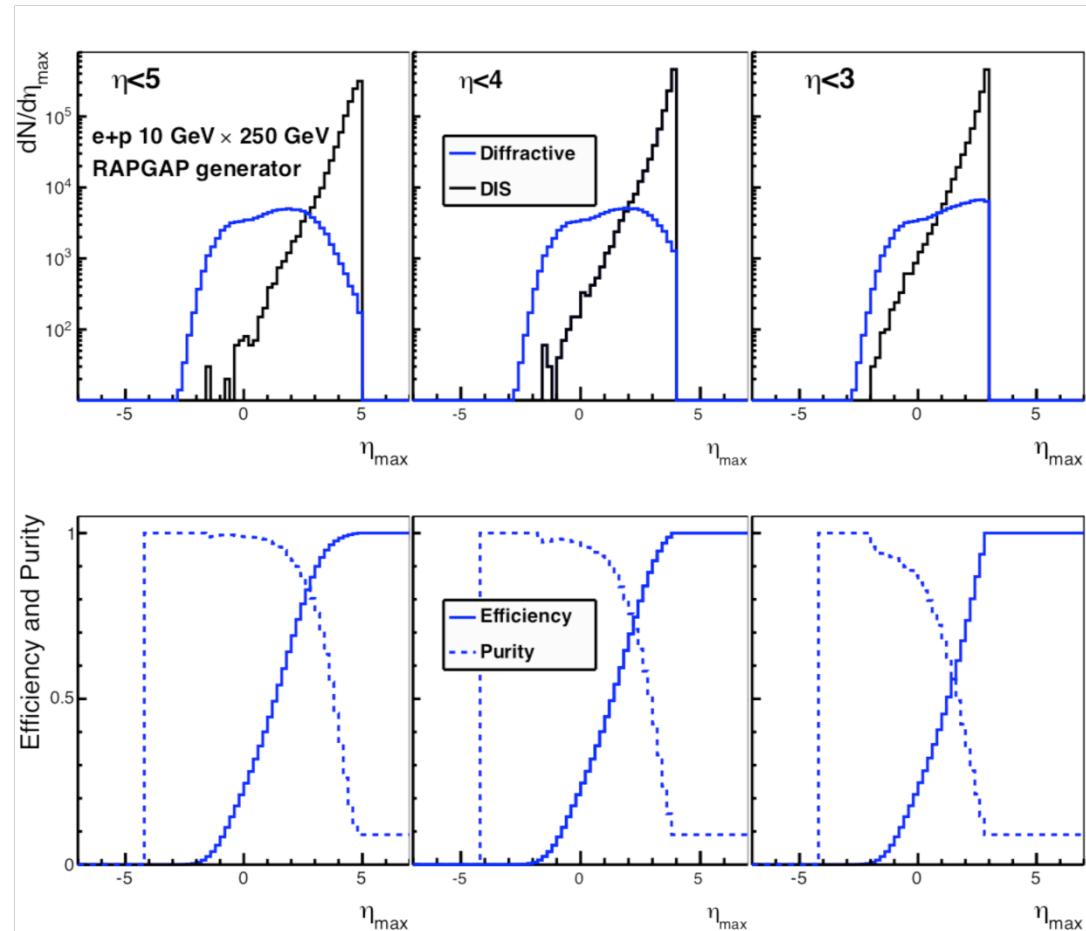
Intact proton detection is highly desirable

Roman Pots



# Diffractive Measurements

- Measure most forward going particle, to determine rapidity gap  
HCal with  $-1 < \eta < 5$  and EMCal with  $-4 < \eta < 4$  are excellent in separation of DIS and diffractive
- ZDC to measure nucleus breakup



# Hadron measurements with HCal and Tracking

At very forward rapidity ( $\eta \sim 4$ ) HCal energy resolution for single tracks may considerably exceed tracking momentum resolution

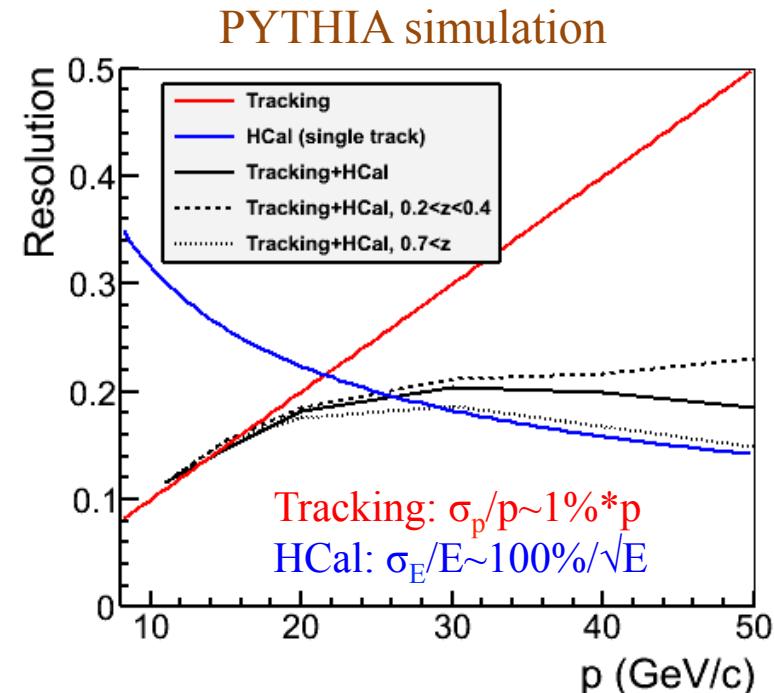
Can HCal be used to measure energy (momentum) of high momentum tracks ?

The main concern is that the energy depositions of tracks in vicinity of a given track are merged in a single cluster in HCal (non-separable in HCal)

The idea:

Usual event structure is that there is one high momentum leading particle with a few lower momentum particles;

Low momentum particles are supposed to be well reconstructed with tracking, so their contribution in HCal can be evaluated and subtracted to calculate the energy deposition of the leading high momentum particle.



Full GEANT4 simulation is ongoing  
The main impact is expected from tracking eff. and ghost (high momentum) tracks

# Hadron PID: Aerogel

Allows to identify K for  $3 < p < 10 \text{ GeV}$

## Challenges:

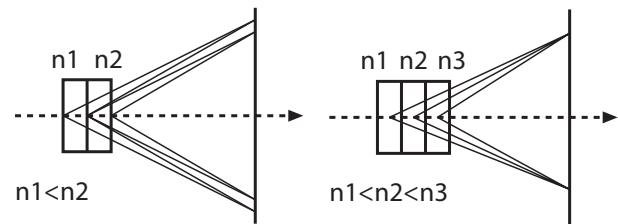
Fringe field

Low light output

Visible wavelength range

Limited space for light focusing

## Focusing



## Photon detection:

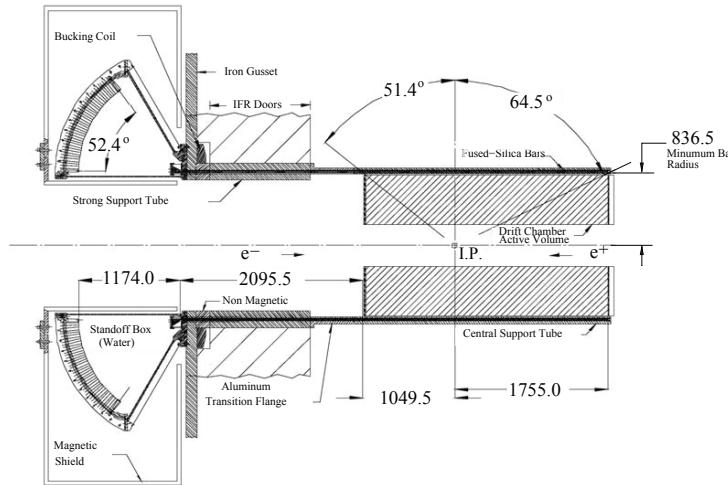
Microchannel Plate Detector

Multi-alkali photocathode

Also ToF with  $\sigma=20-30\text{ps}$

Being developed by  
LAPPD Collaboration

# Hadron PID: DIRC

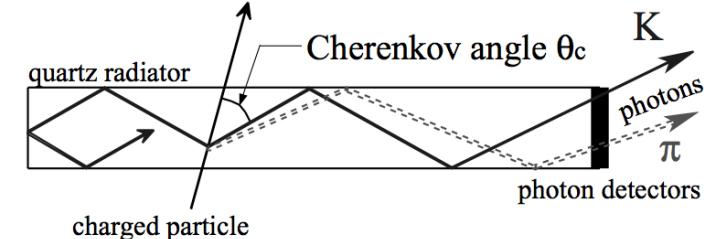


## BaBar DIRC

Quartz radiator bars, Cerenkov light internally reflected

No focusing => Large water filled expansion volume

PMT for readout



## ePHENIX DIRC

Mirror Focusing to avoid large expansion region

Pixelated multi-anode PMT for readout

Ring resolution limits PID at higher  $p_T$

# Inclusive DIS and Kinematics

## Resolutions for $(x, Q^2)$

$$\frac{\sigma_{Q^2}}{Q^2} = \frac{\sigma_{E'}}{E'} \quad \frac{\sigma_x}{x} = \frac{1}{y} \frac{\sigma_{E'}}{E'}$$

Angle resolution provided by EMCAL position resolution doesn't affect  $(x, Q^2)$  resolution

Defines the precision of unfolding technique to correct for smearing due to detector effects

Results in statistics migration from bin to bin  
→ bin survival probability

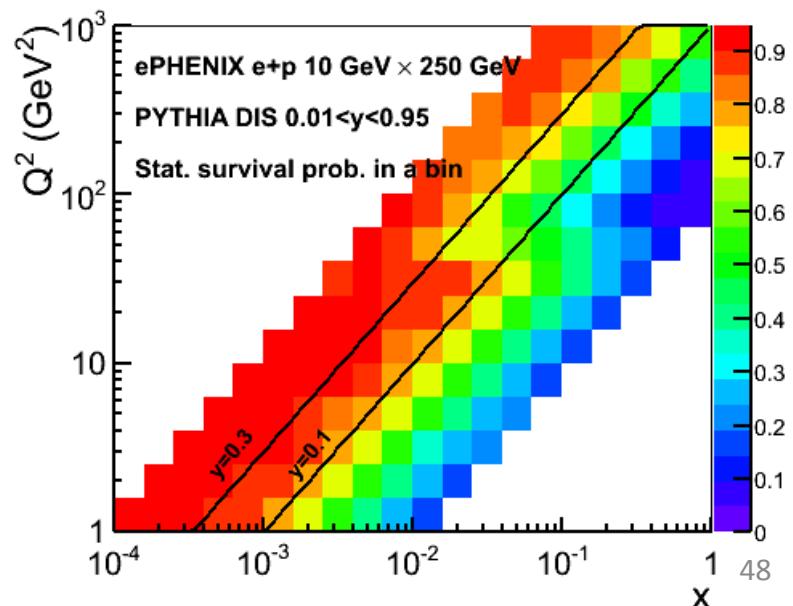
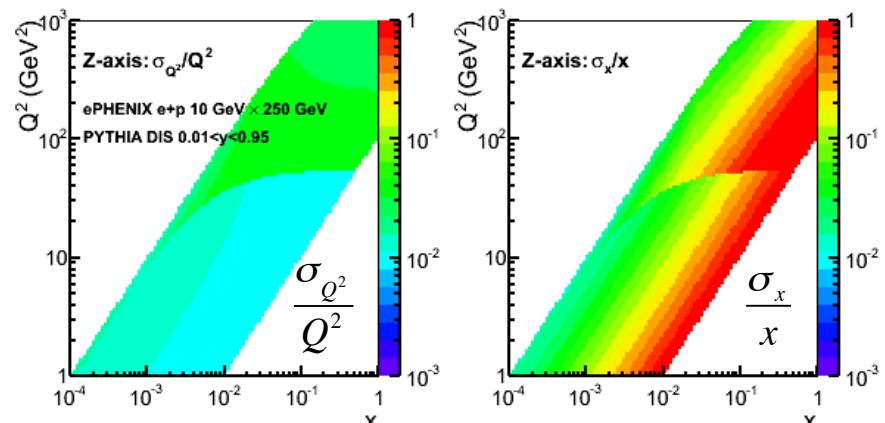
From HERMES experience: ~80% needed

Jacquet-Blondel method (with hadronic final state) will help at lower  $y$  and higher  $Q^2$

Bremsstrahlung radiation: no sizable effect

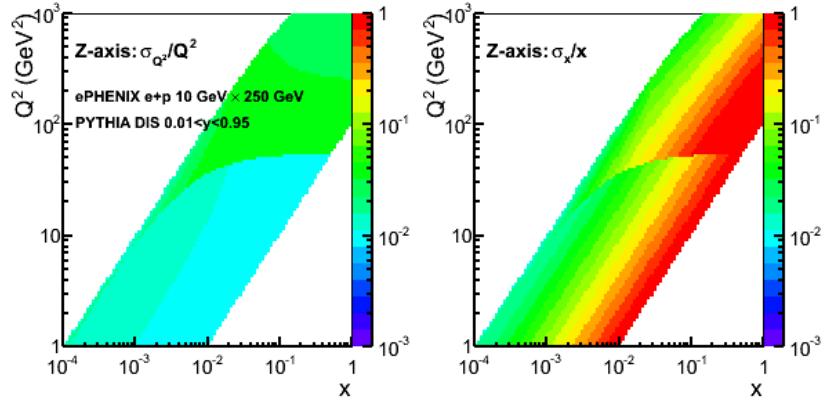
Minimal material

GEANT4: 3-7% impurity for  $y=0.5-0.95$

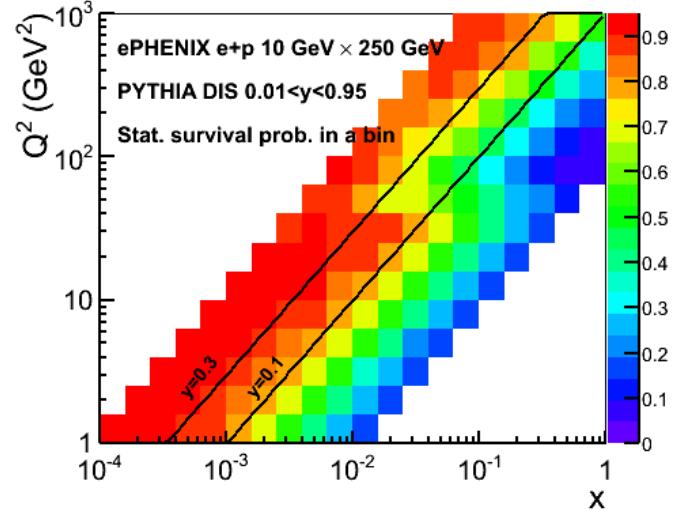
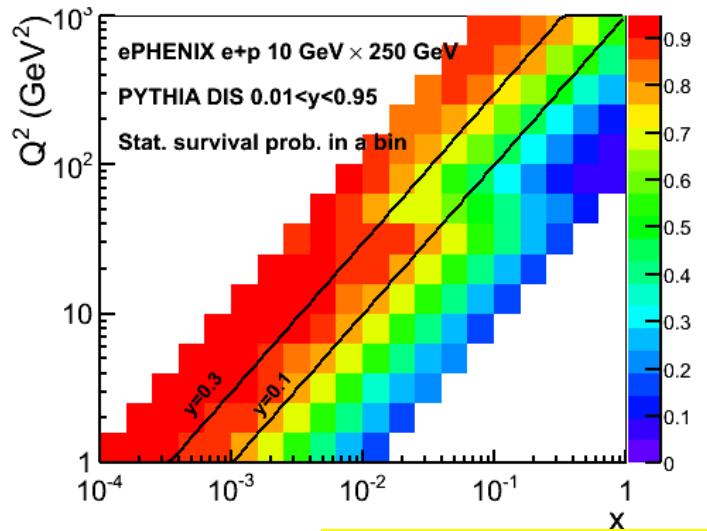
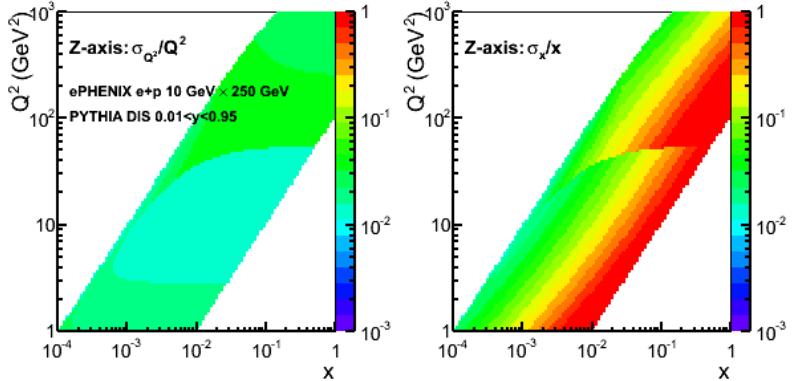


# DIS kinematics: angle from EMCAL

With perfect angle measurements



With angle smearing due to EMCAL pos. resolution



Only minor effect from angle measurements with EMCAL

# Inclusive DIS and Kinematics

## eID and background rejection

### Hadron rejection:

EMCal energy response and E/p

$\times 20\text{-}30$  at 1 GeV/c

$\times 100$  at 3 GeV/c

EMCal shower profile

Expect  $\times 3\text{-}10$

Not yet included in plots

EMCal long. segmentation and/or  
preshower

For future considerations

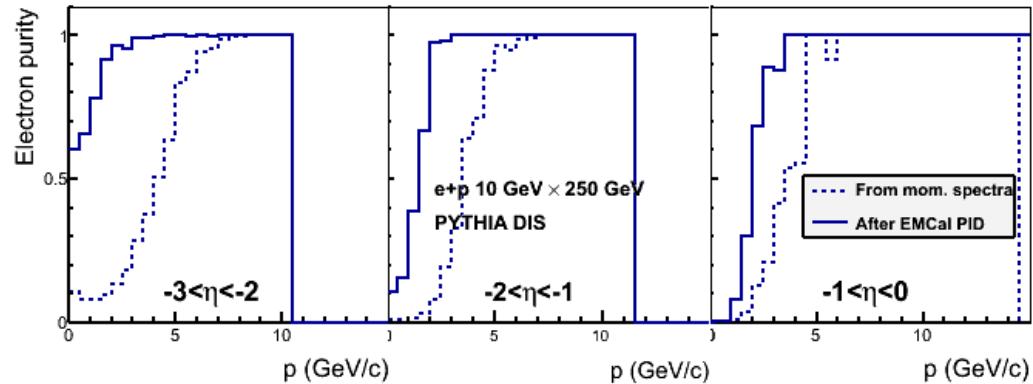
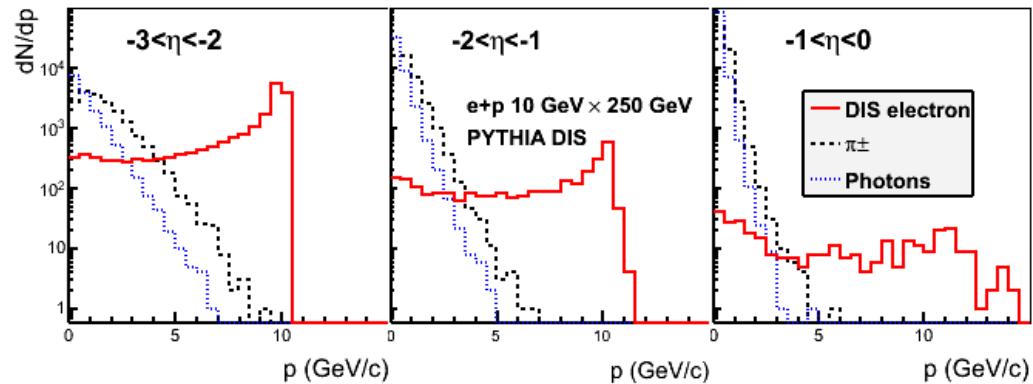
### Photon rejection ( $\gamma \rightarrow e^+e^-$ )

Minimal material

GEANT4 studies:

$>3$  GeV/c: background negligible

$<3$  GeV/c: rejected with tracking+EMCal



Reliable eID down to

$p=2$  GeV/c for 10 GeV e-beam

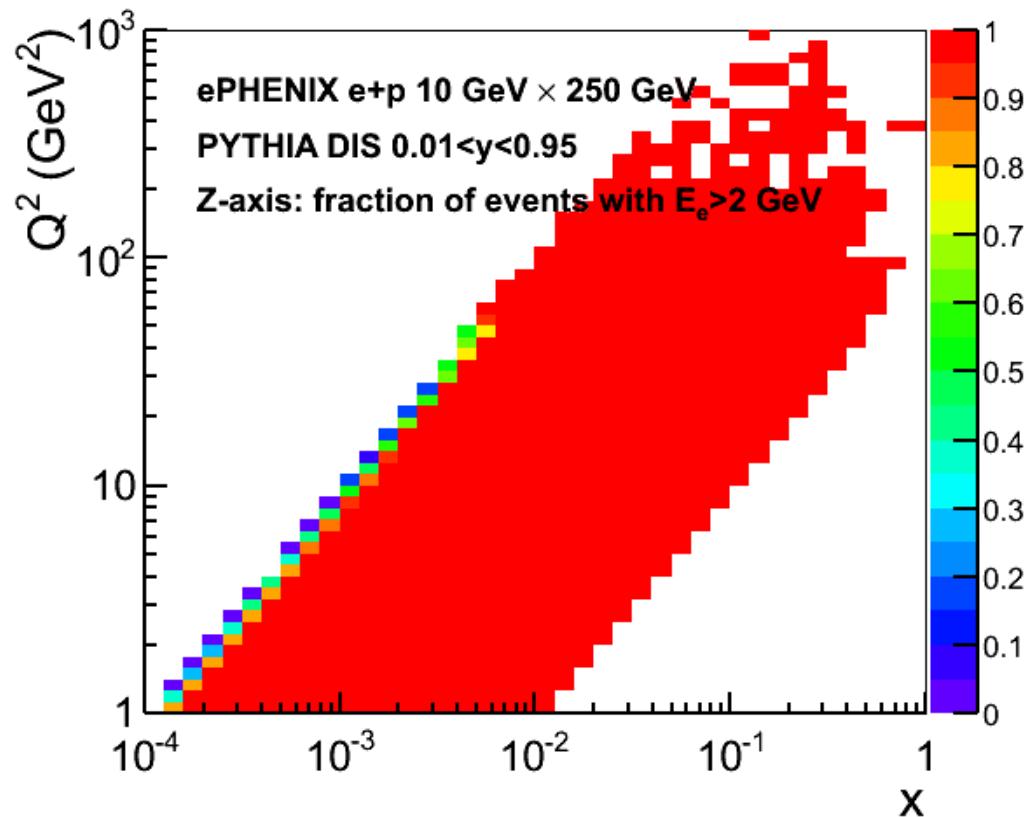
$p=1$  GeV/c for 5 GeV e-beam

Negligible effect on the probed  $(x, Q^2)$  space

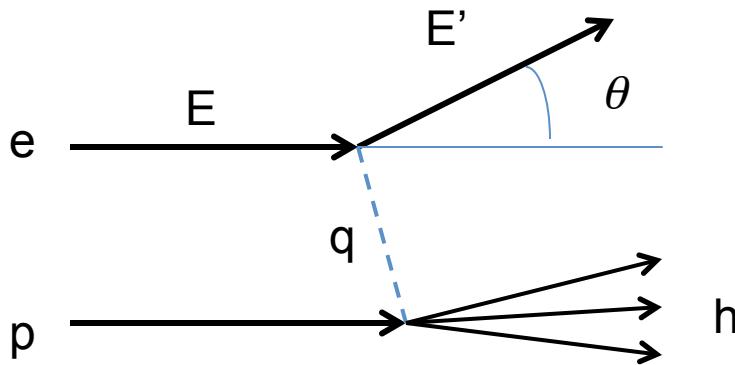
# Inclusive DIS and Kinematics

What if poor eID at  $<2$  GeV/c

Don't lose much of  
the  $(x, Q^2)$  space



# Electron vs Jacquet-Blondel



Electron

$$Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E} \cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

$y \rightarrow 0$ :  $\sigma_y/y \sim 1/y$

JB

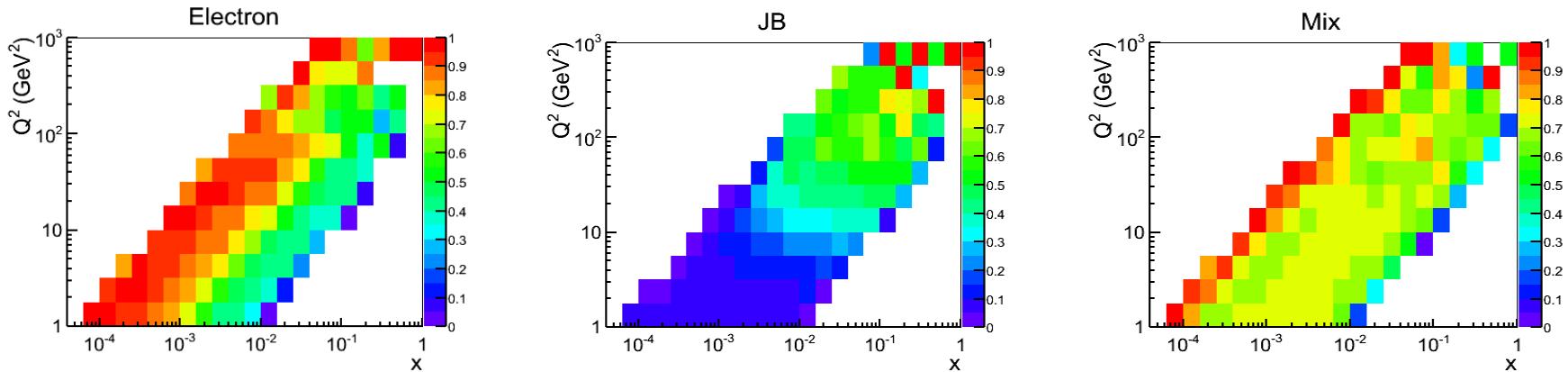
$$Q_{JB}^2 = \frac{p_{T,h}^2}{1 - y_{JB}} \quad p_{T,h}^2 = \left( \sum_h p_{x,h} \right)^2 + \left( \sum_h p_{y,h} \right)^2$$

$$y_{JB} = \frac{(E - p_z)_h}{2E_e} \quad (E - p_z)_h = \sum_h (E_h - p_{z,h})$$

$$x_{JB} = \frac{Q_{JB}^2}{sy_{JB}}$$

$y \rightarrow 0$ :  $\sigma_y/y \sim \text{const}$

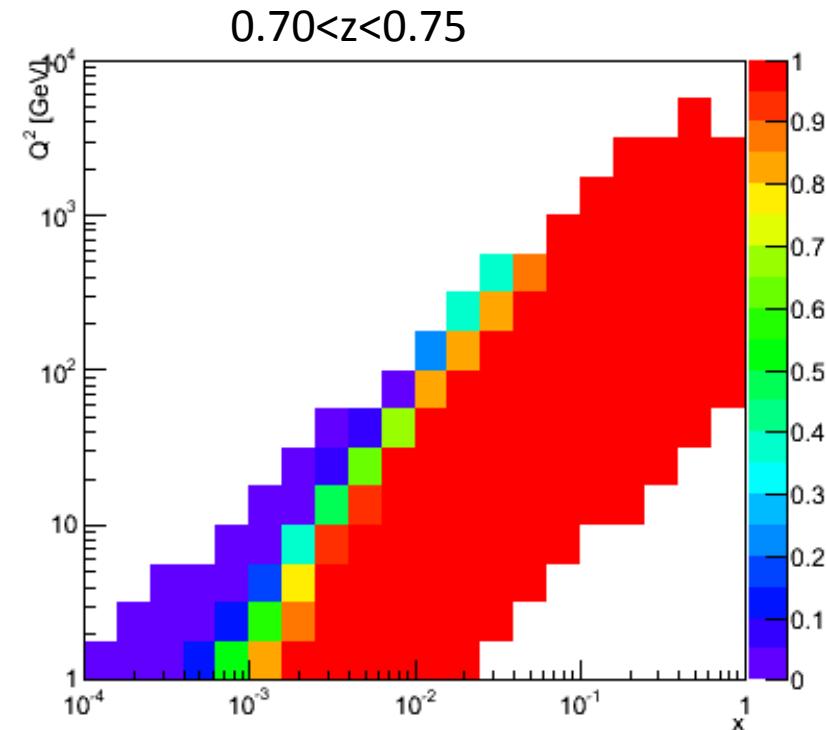
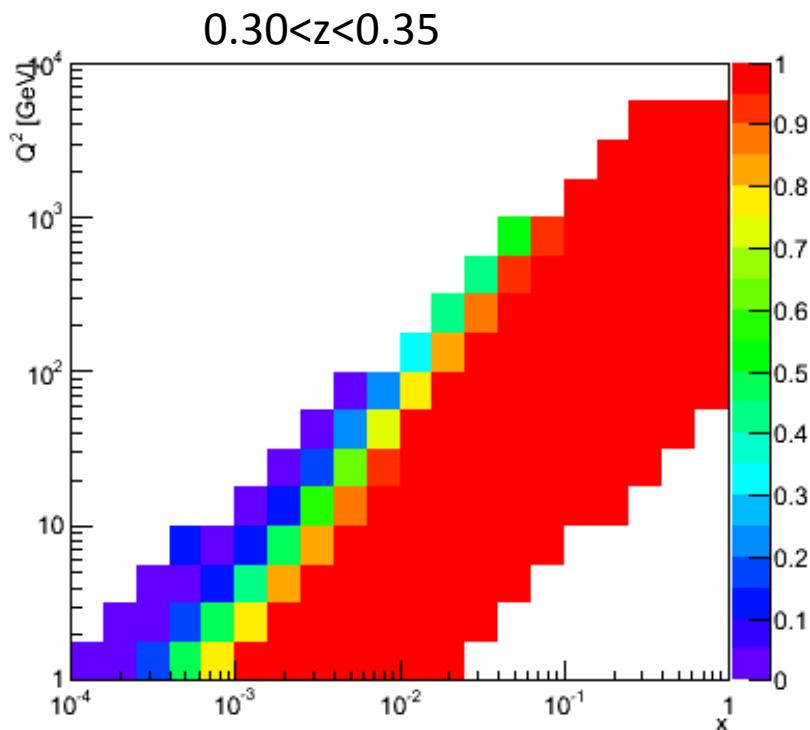
# Electron vs JB vs Mix



For  $15 \text{ GeV} \times 250 \text{ GeV}$  beam energy configuration, event purity in  $(x, Q^2)$  bins, defined by the likelihood of an event to remain in its true  $(x, Q^2)$  bin after resolutions smearing; left – for electron method, middle – for Jacquet-Blondel method, and right – for “Mixed” method, when  $Q^2$  is defined from electron method,  $y$  is defined from Jacquet-Blondel method, and  $x=Q^2/(sy)$ .

# $(x, Q^2)$ loss due to no ePID in e-going direction

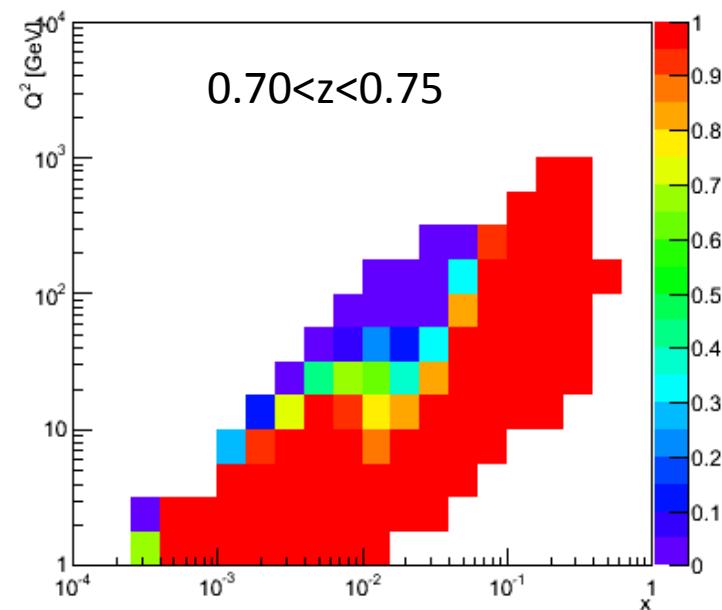
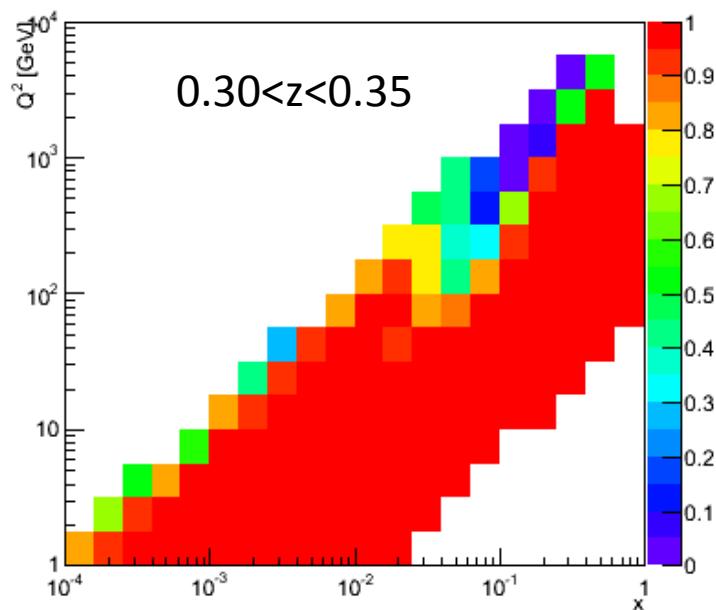
e+p 10 GeV  $\times$  250 GeV  
PYTHIA DIS  $0.01 < y < 0.95$   $W^2 > 10 \text{ GeV}^2$



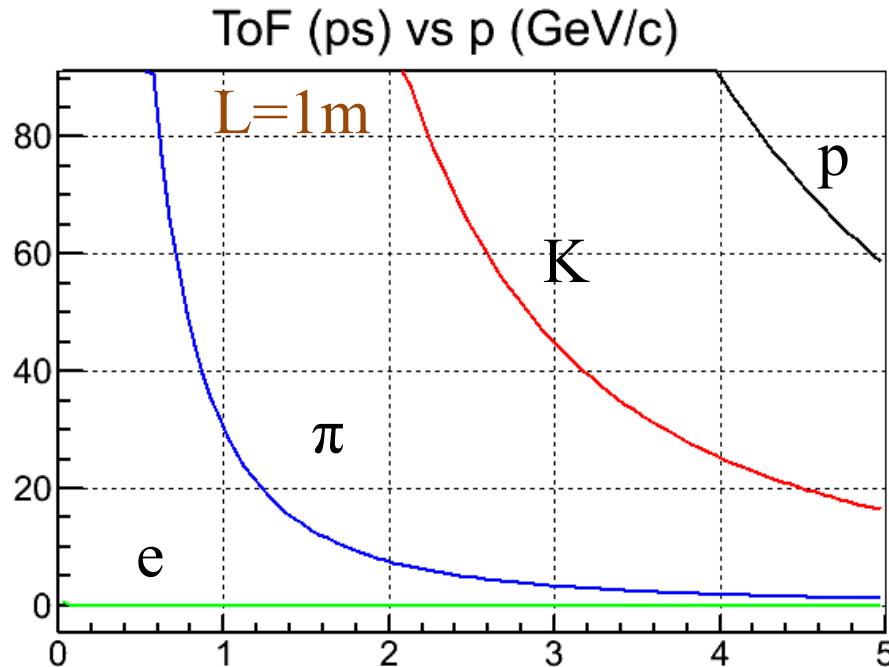
# If better DIRC?

e+p 10 GeV  $\times$  250 GeV  
PYTHIA DIS  $0.01 < y < 0.95$   $W^2 > 10 \text{ GeV}^2$

“Normal” DIRC:  $\pi/K$  separation up to  $3.5 \text{ GeV}/c$   
Improved DIRC:  $\pi/K$  separation up to  $6 \text{ GeV}/c$



# ToF for PID?



With 10 ps resolution including  $t_0$ :

$e/\pi$  separation at  $<1 \text{ GeV}/c$

$K/\pi$  separation at  $<4 \text{ GeV}/c$

Need  $t_0$  ( $\sigma < 10 \text{ ps}$ ) and vertex ( $\sigma \sim 1 \text{ mm}$ )

# From 10 to 20 GeV e beam

## ePHENIX Lol considerations

### Scattering electron kinematics

Need eID at  $\eta < -3$

### Scattered electron ID

Tracking may not be needed at  $\eta < -3$ ; charge veto still needed

### Q2&x resolution

No deterioration expected

### SIDIS (hadron measurements):

barrel and h-going direction: mainly defined by hadron beam energy =>  
all conclusions in ePHENIX Lol are valid for 20 GeV electron beam

e-going direction: not considered in Lol; may need a look

### Exclusive DIS

No show stopper identified (e.g. for DVCS)

### Diffractive (rapidity gap):

Don't expect any change – depends mainly on hadron beam

# ePHENIX: Cost and schedule

Table 4.1: Estimated equipment costs for the ePHENIX detector (in \$M).

|                          |                   | Cost  | Overhead | Contingency | Total |
|--------------------------|-------------------|-------|----------|-------------|-------|
| Calorimeters             | Endcap Crystal    | 3.40  | 0.47     | 1.93        | 5.80  |
|                          | Forward EMCAL     | 1.41  | 0.27     | 0.84        | 2.53  |
|                          | Forward HCAL      | 3.90  | 0.68     | 2.29        | 6.87  |
| Tracking                 | TPC               | 0.75  | 0.19     | 0.47        | 1.41  |
|                          | GEM Trackers      | 0.71  | 0.18     | 0.44        | 1.33  |
| Beamline instrumentation | Roman pots        | 0.23  | 0.04     | 0.14        | 0.41  |
|                          | Beam-Beam counter | 0.20  | 0.05     | 0.13        | 0.38  |
| Particle ID              | DIRC              | 12.50 | 1.75     | 7.13        | 21.38 |
|                          | RICH              | 2.00  | 0.50     | 1.25        | 3.75  |
|                          | Aerogel           | 1.55  | 0.22     | 0.88        | 2.65  |
| Electronics/sensors      | Endcap Crystal    | 0.89  | 0.22     | 0.56        | 1.67  |
|                          | Forward EMCAL     | 3.09  | 0.43     | 1.76        | 5.28  |
|                          | Forward HCAL      | 0.38  | 0.05     | 0.22        | 0.65  |
|                          | TPC               | 2.80  | 0.81     | 1.81        | 5.42  |
|                          | GEM Trackers      | 0.71  | 0.18     | 0.44        | 1.33  |
|                          | DIRC              | 0.77  | 0.19     | 0.48        | 1.44  |
|                          | RICH              | 0.69  | 0.17     | 0.43        | 1.29  |
|                          | Aerogel           | 1.55  | 0.39     | 0.97        | 2.91  |
|                          | Roman Pots        | 0.11  | 0.03     | 0.07        | 0.21  |
|                          | Beam-Beam         | 0.10  | 0.02     | 0.06        | 0.19  |
|                          | Data Collection   | 0.60  | 0.15     | 0.38        | 1.13  |
| Integration/Mechanical   | Trigger           | 0.60  | 0.15     | 0.38        | 1.13  |
|                          |                   | 3.00  | 0.93     | 1.96        | 5.90  |
| Total                    |                   | 41.94 | 8.08     | 25.01       | 75.02 |

Table 4.2: Total estimated labor for ePHENIX detector construction.

|                 | FY21 | FY22 | FY23 | FY24  | Total |
|-----------------|------|------|------|-------|-------|
| Physicist FTE   | 10   | 9    | 10   | 13    | 42    |
| Physicist cost  | 3.02 | 2.78 | 3.45 | 4.60  | 13.85 |
| Engineer FTE    | 10   | 10   | 7    | 5     | 31    |
| Engineer cost   | 2.59 | 2.66 | 2.02 | 1.49  | 8.76  |
| Technician FTE  | 1    | 1    | 11   | 19    | 31    |
| Technician cost | 0.21 | 0.21 | 2.29 | 4.16  | 6.87  |
| Total FTE       | 20   | 19   | 28   | 37    | 104   |
| Total cost      | 5.81 | 5.65 | 7.77 | 10.25 | 29.49 |

Table 4.3: Schedule of Critical Decisions and reviews necessary for construction FY2021–FY2024.

|                        |                 |
|------------------------|-----------------|
| CD0                    | 4Q2016          |
| CD1 review             | 4Q2017          |
| TDR preparation        | 4Q2017 - 3Q2019 |
| CD2/3 review           | 4Q2019          |
| FY2021 budget briefing | 1Q2020          |
| Construction start     | 4Q2020 (FY2021) |
| CD4                    | 3Q2024 (FY2024) |
| Commissioning run      | 1Q2025          |

# fsPHENIX

As from last year's PHENIX "Future opportunities for p+p and p+A at RHIC"

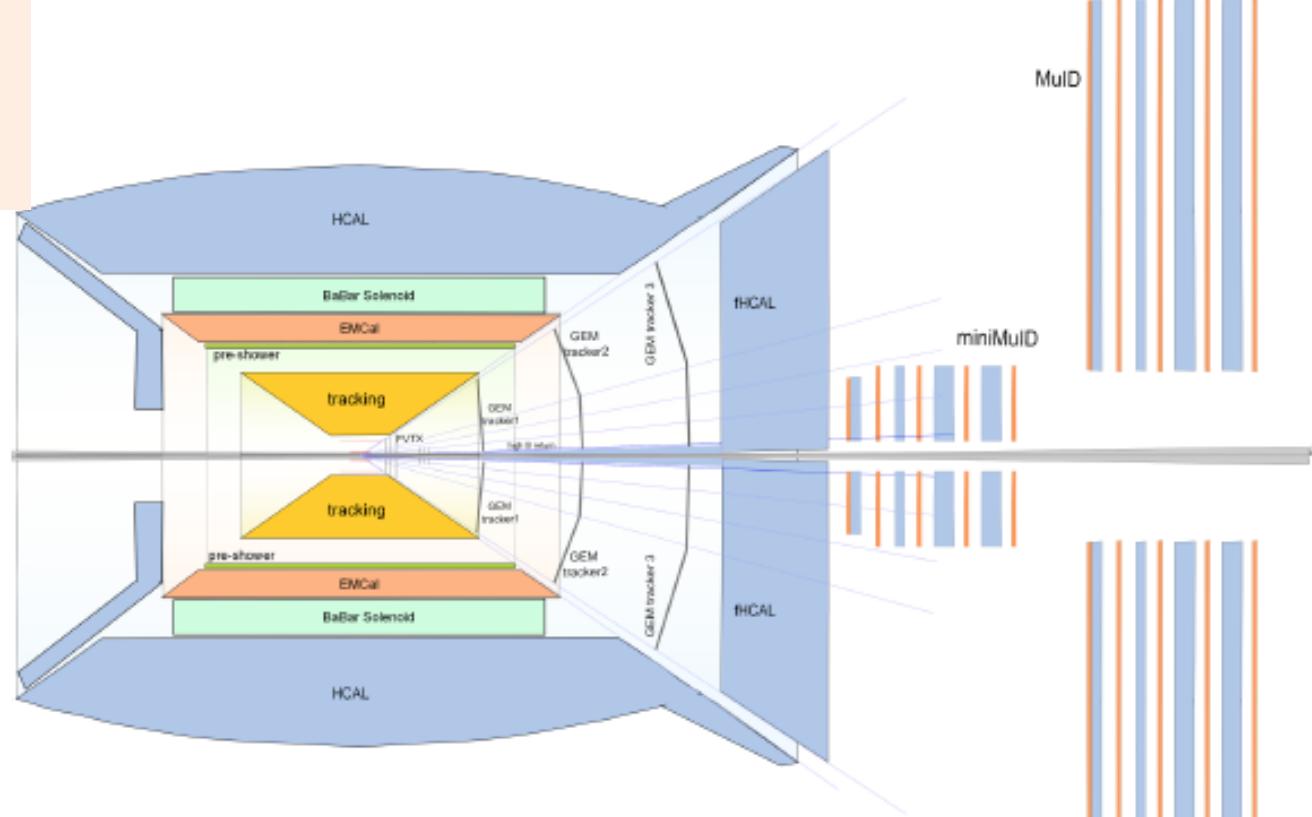
## Build:

HCal

GEM trackers

Mini-MUID ( $2.4 < \eta < 4$ )

Passive Field shaper



## Re-use:

FVTX

MUID ( $1.2 < \eta < 2.4$ )

# fsPHENIX

## Tracking ( $1 < \eta < 4$ ):

Inner tracker: reconfigured PHENIX FVTX at  $z=20\text{--}70$  cm

Intermediate tracker: 3 GEM planes at  $z=150, 200$  and  $300$  cm

Large area GEM foils under development at CERN

Los Alamos group is interested and looking for funds

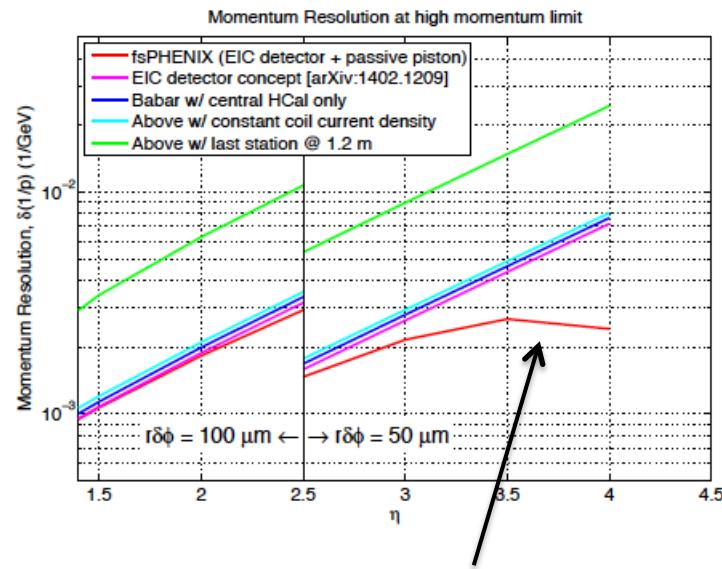
## HCal ( $1 < \eta < 5$ )

Steel-scintillating tile

$\sigma_E/E < 100\%/\sqrt{E}$

RIKEN group is interested and looking for funds

Building of smaller systems ( $2 < \eta < 4$ ) is also considered  
(Need to evaluate how much we can save with it)



With field shaping

# fsPHENIX: Cost Estimate

No labor included

**Table 4.1:** Estimated equipment costs for the fsPHENIX upgrade (in \$M).

|                              | Cost | Overhead | Contingency | Total |
|------------------------------|------|----------|-------------|-------|
| HCal                         | 3.90 | 0.68     | 2.29        | 6.87  |
| GEM Tracker                  | 0.67 | 0.17     | 0.41        | 1.25  |
| FVTX reconfiguration         | 0.53 | 0.11     | 0.31        | 0.95  |
| miniMUID                     | 0.13 | 0.03     | 0.08        | 0.24  |
| Piston Field Shaper          | 0.06 | 0.02     | 0.04        | 0.12  |
| HCal electronics/sensors     | 0.38 | 0.05     | 0.22        | 0.65  |
| GEM electronics/sensors      | 0.63 | 0.16     | 0.39        | 1.18  |
| miniMUID electronics/sensors | 0.05 | 0.01     | 0.03        | 0.09  |
| MUID trigger electronics     | 0.35 | 0.07     | 0.21        | 0.63  |
| Total                        | 6.7  | 1.3      | 3.98        | 11.98 |